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Working Group on the Use of Nuclear
Power Sources in Outer Space

USE OF NUCLEAR POWER SOURCES IN OUTER SPACE

Note by the Secretariat

Annexed hereto is a study submitted by the Federal Republic of Germany on safety aspects of nuclear power sources in outer space. It is being circulated, as received, only in the language of its submission (English).

Annex

SAFETY ASPECTS OF NUCLEAR POWER SOURCES IN SPACE

Executive Summary

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1. INTRODUCTION

This paper presents results of a joint research- and development project of Institut fuer Raumflugtechnik und Reaktortechnik (IfRR) and Gesellschaft für Reaktorsicherheit (GRS) sponsored by the Federal Minister for Research and Technology in an effort to evaluate the hazard resulting from nuclear power systems operated in space. The project is intended to contribute to the international discussion within the United Nations with respect to the work on safety criteria for nuclear power sources (NPS) in space.

When Nuclear Power Sources (NPS) are operated in space, a series of aspects specific to orbit mechanics and spaceflight technology must be discussed in order to determine and assess the safety problems. Some of these aspects are beyond the safety considerations for terrestrial applications:

- the world-wide importance of the safety-problem, as soon as the space object with NPS on board has reached an earth orbit. The effects of certain functional errors can lead to a risk for any territory on the earth's surface, which cannot be located before the re-entry, and to a global negative effect on the upper atmosphere;
- the lack of the possibility of manned assistance on orbit in the case of a failure (in the present state of space technology).

The results of the orbit mechanical analysis carried out by the Institut fuer Raumflugtechnik und Reaktortechnik (IfRR) have been submitted to the Gesellschaft fuer Reaktorsicherheit (GRS) in order to enable a subsequent radiological assessment of NPS missions.

The main goal of this study is not an analysis of specific existing (or planned) NPS types and missions but the general identification of mission related parameters,that can lead to radiological hazards.

In Fig. A and B an overview on mission with NPS on board (including their phases, manoeuvres and possible malfunctions) is given. The items that have been examined within this study are marked.

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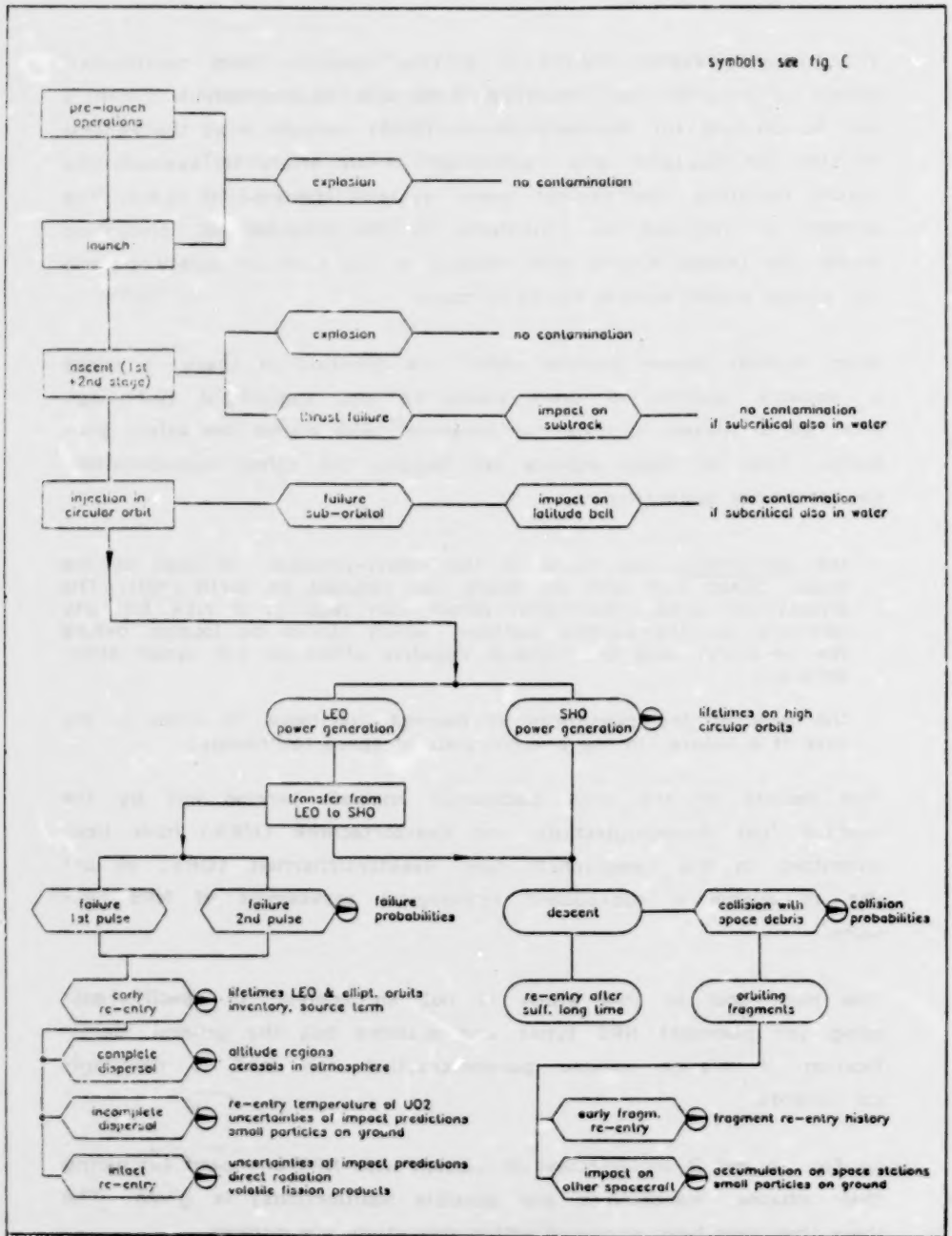
symbols see fig. C
pre-launch operations
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explosion
no contamination
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explosion
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injection in circular orbit
failure sub-orbital
impact on latitude belt
no contamination if subcritical also in water
LEO power generation
SHO power generation
lifetimes on high circular orbits
transfer from LEO to SHO
failure 1st pulse
failure 2nd pulse
failure probabilities
descent
collision with space debris
collision probabilities
early re-entry
lifetimes LEO & ellipt. orbits inventory, source term
re-entry after suff. long time
orbiting fragments
complete dispersal
altitude regions aerosols in atmosphere
incomplete dispersal
re-entry temperature of UO2 uncertainties of impact predictions small particles on ground
intact re-entry
uncertainties of impact predictions direct radiation volatile fission products
early fragm. re-entry
fragment re-entry history
impact on other spacecraft
accumulation on space stations small particles on ground
IRR TUBS
EVENTS WITH NUCLEAR REACTORS
Fig. A
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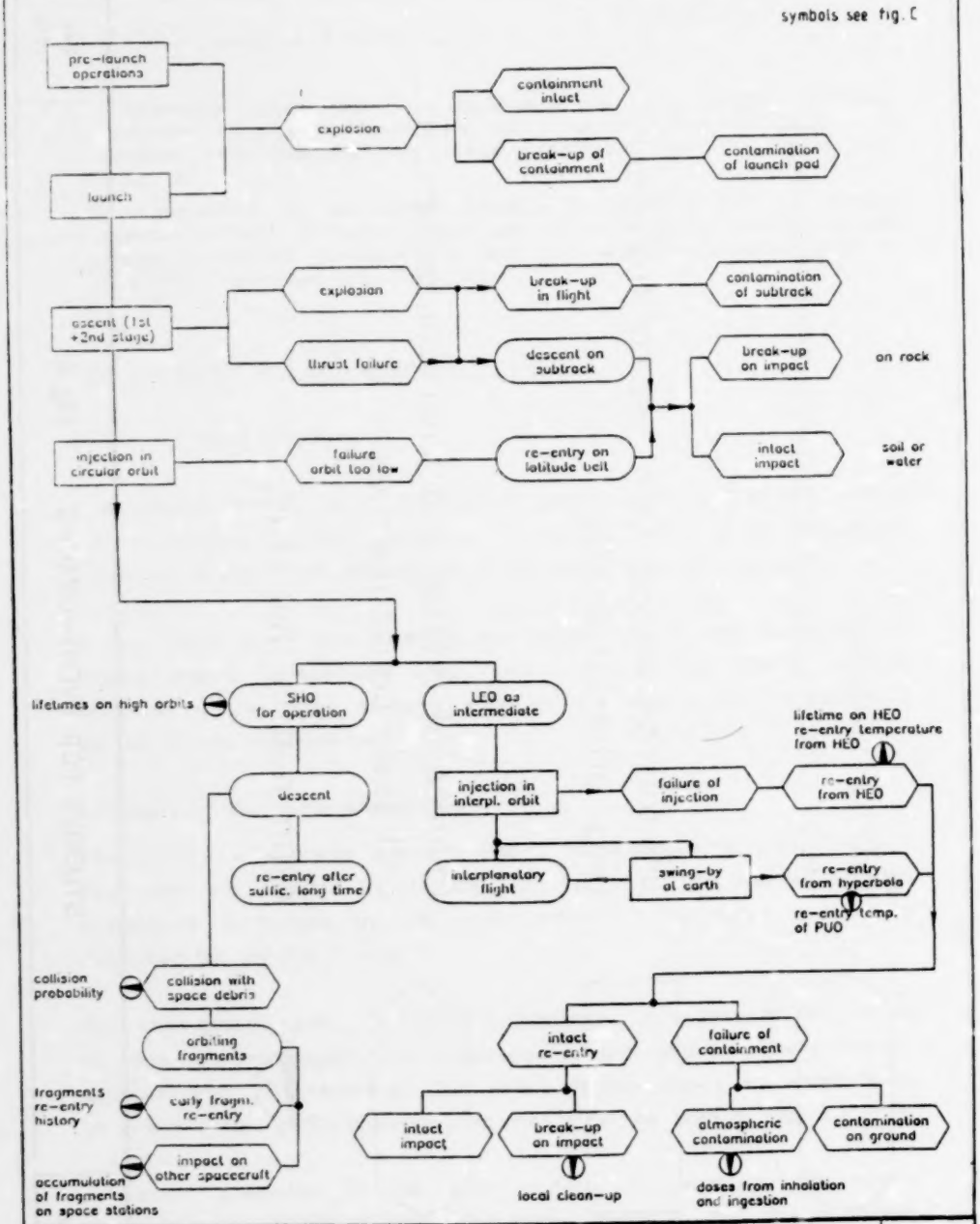

IRR TUBS	EVENTS WITH ISOTOPE GENERATORS IN CONTAINMENT	Fig. B	1989

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orbital situation
(e.g. circular orbit, natural descent etc.)

orbital operations, (e.g. orbital transfer)
(e.g. orbital transfer)

failures of orbital and their consequences
and their consequences

examined in this study

IfRR TUBS	SYMBOLS FOR EVENT-GRAPHS Fig.C	Dez. 1989

2. ORBIT MECHANICAL ASPECTS

The analysis consists of the following two parts:

- fundamental orbit mechanical considerations (e.g. orbital lifetimes, re-entry behavior of materials etc.) which apply in general to present NPS missions and those imaginable for the future (cf. chap. 2);
- considerations on the safety aspects of missions with a nuclear reactor or with a radio-isotope generator on board concerning the above mentioned fundamentals and the specific characterictics of the NPS types used (cf. chap. 3).

2.1 Ascent and orbital phases of NPS

2.1.1 Orbital lifetimes

The orbital lifetime of a satellite in earth orbit is the time which elapses, taking an initial orbit as a starting point, until the object burns up in the upper atmosphere or reaches the earth's surface.

During this time, the satellite is exposed to a continuos loss of energy due to atmospheric drag. The extent of this loss of energy depends on the mass to area ratio of the object and on the local density of the atmosphere.

▪ Density of the upper atmosphere

The earth's atmosphere shows a nearly exponential decrease in density with an increase in altitude (cf. Fig. 1). The density is also subject to variations by the solar activity. The solar activity is described by the F10.7 value.

For the determination of satellite lifetimes in orders of magnitude of some hundred years, the konwledge of the long-term behaviour of solar activity is necessary. The solar activity shows an approximate 11 years' cycle. Distinct maxima and minima can be seen in Fig. 2.

An exact prediction of the solar activity is especially not possible for short periods of time. The model shown in Fig. 2 was chosen

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for future solar activity. This model represents a worst case scenario of the solar activity for the calculation of orbital lifetimes in the order of magnitude of some hundred years. "Worst case" in this context means that the orbital lifetimes computed represent the lower limit and will, with a high degree of probability, not be fallen below in practice.

• Circular orbits with a nominal lifetime longer than 70 years (lower limits)

Fig. 3 shows the lifetimes of objects on nearly circular orbits versus their initial altitudes, where the nominal lifetime is longer than 70 years and does not depend on the point in time within the solar cycle at which a mission begins (averaging effect).

The lifetimes in this altitude range are nearly proportinal to the ballistic coeffient. As to the radiological assessment lifetimes of 300 years are being discussed concerning the parking orbits of nuclear reactors. As can be seen from fig.3 such a lifetime would, for example, require an initial orbital altitude of about 800 km for a satellite which has a ballistic coefficient of 200 kg/m^2.

• Circular orbits with a nominal lifetime less than 70 years

For nominal lifetimes less of than 70 years, there is an influence of the point in time within the solar cycle at which the mission begins (the averaged solar activity is not constant).

Lifetimes of this order of magnitude play an important role concerning specific malfunctions during a NPS mission as discussed in chap. 3.

Figures 4 through 6 show the lifetime ranges versus the initial altitudes related to a ballistic coefficient of 100 kg/m^2. As can be seen, for example, from fig.5 the lifetime at an altitude of 260 km can differ by the factor 2.5 due to the solar activity.

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▪ Lifetimes on elliptical transfer orbits

The transfer orbits from a low earth orbit to a parking orbit play another significant role concerning the possible malfunctions during a NPS mission as discussed in chap. 3.

As can be seen from fig. 7, the lifetimes on these orbits vary from less than half a year to about 9.5 years, depending upon the parameter combination (apogee and perigee altitude, solar activity and ballistic coefficient).

▪ Lifetimes on highly eccentric orbits

Highly eccentric orbits, which can occur due to malfunctions during a deep space mission (cf. chap. 3), are subject to very strong influences of lunisolar pertubations (gravity of sun and moon).

Depending upon the astronomical situation orbital lifetimes between practically zero and more than 15 years are possible. Fig. 8 shows examples of such lifetimes due to some specific initial configurations.

▪ Summary concerning orbital lifetimes

The orbital lifetimes of satellites with NPS on board play a significant role on

- the mission planning,
  e.g. the altitude of the operational or the parking orbit of a nuclear reactor, so that the activity of the fission and activation products can decay sufficiently before they re-enter the earth's atmosphere;
- the time until re-entry in the case of a malfunction,
  which has an influence on the radiological hazard and the warning time available.

The orbital lifetimes of satellites can only be altered, if there is an active propulsion system available. That means that from a certain phase of the mission the orbital lifetime is definitely determined and depends only on the current initial altitude and the ballistic coefficent, since the solar activity history can not be influenced.

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2.1.2 Collisions of NPS with space debris - probalility and consequences

It is a well known fact that near earth space is crowded with man made objects, mainly pieces of space debris, causing a collision risk increasing with time. The impact of such space debris objects on a spacecraft leads to major damage due to the high relative velocities.

The use of spacecraft with NPS on board in this space debris environment requires detailed analysis of the the probability and the consequences of a collision between a NPS object and space debris and the subsequent assessment of the radiological hazard of such an event.

- Current object density and resultant collision probability

In fig. 9 the current collision probability as function of orbital altitude is given. Space debris objects larger than 1 cm in diameter are taken into consideration.

As can be seen from the figure, object density and collision probability show a maximum plateau in the altitude range between 700 and 1000 km. This is, at the same time, the range of altitudes that would ensure sufficient orbital lifetime for a spacecraft with a nuclear reactor on board (cf. chap. 2.1.1).

- Assessment:

If we presume that the numbers of space debris objects will not increase in the future, than a residence time of 300 years in this area of altitude leads to a collision probability of 0.5 % per m^2. This means a collision probability of 2.5 % for a satellite of 5 m^2 cross-section.

If for 50 years 2 satellites per year with a reactor on board will be launched into this altitude region, then, from the statistical point of view, two to three of them will have a collision within 300 years under the conditions listed above.

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However, an increase in the object density will have to be taken into account in the future. The extent of this increase depends primarily upon the general development of space activities and of space technology (e.g prevention of explosions).

Fig.10 shows the number of impacts that accour on a surface of 1 m^2 stored at an orbital altitude of 1000 km for 300 years, with certain growths factors of the object density. Trends for a linear and a progressive increase of the number of space debris objects are shown. As can be seen from the figure, under certain conditions one or more impacts per m^2 will be probable.

Under these conditions each of the reactors stored for 300 years in these altitudes would have a collision with space debris. This example shows the sensitivity of the space debris problem according to the future development.

- Consequences of a collision

In a collision in space of the kind discussed, the relative velocities amount up to 13 km/s. The mean collision velocity is about 10.5 km/s, which corresponds to 37,800 km/h or 32 times the speed of sound on the earth's surface (cf. fig. 11). These high collision velocities give even fairly small particles (1 cm) the potential to destroy a satellite in earth orbit. The angle distribution of the impacting object flux is given in fig. 12.

In the following, a complete destruction of a nuclear reactor and the subsequent history of the fragments is simulated.

A collision initially results in a cloud of fragments. Fig. 13 shows how the orbits of 100 collision fragments produced in a simulation are distributed almost uniformly around the earth in a spherical shell within 2 years.

The orbit of the collision fragments were computed using orbit mechanical programs and the point in time of their respective reentry into the earth's atmosphere was recorded. Fig. 14 shows the total mass returning to earth during the time after the collision.

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In this example, 97 % of the initial mass entered the denser layers of the earth's atmosphere within 25 years.

This earlier re-entry is due to the fact that the mean ballistic coefficient of the collision fragments is considerable smaller than that of the intact spacecraft (and that of the NPS).

In the most unfavourable case, 97 % of the mass (e.g. of a nuclear reactor) enter the earth's atmosphere as soon as 25 years after switching-off of the reactor. The radio-active fragments show a re-entry behaviour not defined by the original design. Both a dispersal of the fragments as well as their intact re-entry are possible. The radiological consequences from a premature re-entry are dealt with in chapter 4.2 contributed by GRS.

The numbers and sizes of fragments generated by a collision is not really predictable. Under the assumption of a hyper velocity collison up to some billion of fragments with a diameter smaller than 1 mm may be generated. During their natural orbital descent these fragments reach the altitude ranges where manned space structures are operating (for example at 500 km altitude).

Fig.15 shows the mass accumulated on the surface of such a space structure due to small impacting radio-active fragments as function of time and mean fragment diameter.

While this mass fraction of the reactor fuel is so small that a direct radiological hazard is not involved, it may however have an impact on the operations on board a space structure in order to avoid direct skin contact, incorporation and interferences with experiments in space.

- Summary concerning the collisions of NPS with space debris

Due to the fact that a large number of radio-active fragments with a reduced orbital lifetime is produced in a collision involving a NPS object, mission with NPS on board, which are designed for a long period of time (e.g. reactors on a parking orbit), should be planned so that

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- the collision probability is minimized;
- if a collision occurs, the fragments generated have a lifetime that enables sufficient radio-active decay of the fission products.

This goal can be reached by using orbits higher than postulated in chap. 2.1.1, which then have a lower collison probability and a longer orbital lifetime.

2.2 Accidental re-entry of NPS

2.2.1 Prediction uncertainties concerning the point in time and location of NPS re-entry

An accidental re-entry of a spacecraft with NPS on board will occur within a specific latitude belt due to the inclination of the orbit as shown in fig. 16. The impact probability within this belt is uniform.

In order to enable countermeasures on the ground, the time and the location of an accidental NPS re-entry are significant parameters. The prediction uncertainties concerning these parameters are mainly influenced by the solar activity (especially solar flares followed by geomagnetic storms) and the precise knowledge of object related data (ballistic coefficient, tracking data). Fig. 17 shows the individual contributions of these influences as function of time until re-entry. As can be seen from the figure the influences of the object related informations gain importance with time.

In practice, the overall prediction uncertainties concerning the time of re-entry amount about ± 10 %. This results in possible re-entry groundtracks as function of the remaining time as shown in fig. 18.

2.2.2 Thermal and mechanical conditions of re-entry

In order to assess the behaviour of nuclear materials during re-entry (melting / evaporation vs. intact re-entry) computer simulations have been performed.

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For simple geometries (spheres in the following examples), the heat flow, temperature and deceleration during re-entry were determined. It was taken into account that the characteristic properties of the materials (emission coefficient, specific heat and thermal conductivity) are dependent upon the temperature.

The calculations have been carried out under the presumptions

- re-entry from a near-circular orbit (the most probable case),
- bare spheres (to establish a maximum heat flow),
- uniform surface properties of the spheres,
- both a stable flight orientation and a tumbling of the spheres during re-entry (resulting in the maximum and minimum thermal stress on a specific area on the surface),

by using two computer programs, i.e, an orbital re-entry simulation and a heat transfer program, which accepts temperature-dependent properties and treats conductive and radiative heat transfer mechanisms.

Temperature and deceleration of a uranium-dioxide sphere of 10 mm in diameter during the re-entry versus the altitude are shown in Fig. 19. The most probable re-entry conditions, a tumbling object re-entering from a near-circular orbit, are assumed. The maximum temperature which the pellet reaches at an altitude of 55 km is nearly 2300 K, whereas the melting temperature of this material amounts 3000-3100 K. Melting does not take place.

If the flight orientation and the diameter of the spheres are varied fig. 20 applies. It can be seen from this figure, that neither upon tumbling nor upon a stable flight orientation during re-entry melting of uranium-dioxide spheres of any diameter takes place. Another significant result is the fact that the maximum temperature strongly depends on the the diameter of the spheres in the range between 0.01 mm and 10 mm. Such diameters are relevant to collision scenarious dicussed in chap. 2.2.2.

The re-entry behaviours of other materials than uranium-dioxide show specific diameter limits beyond which melting takes place.

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If a specific material does melt during re-entry, the altitude at which melting occurs is a function of the mass to area ratio of the sphere. From fig. 21 can be seen, that small spheres reach their maximum heat flow at higher altitudes than larger spheres. The melting can occur before the maximum heat flow is reached, depending upon the material properties. The altitude regions at which melting occurs have been used by GRS for the dispersal calculations (cf. chap. 4.2.2).

If re-entry occurs on a high eccentric orbit (cf. chap. 3.3) the thermal and mechanical loads are even higher. Fig. 22 indicates that, for example, a bare sphere (10 mm) of plutonium-dioxide does not withstand such an event, it starts to melt.

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3. SAFETY ASPECTS OF ORBITAL OPERATIONS WITH NPS

3.1 General considerations and overview

In order to enable the discussion on the safety aspects of NPS orbital operations, tab.1 gives an overview on the various mission types as far as they have been applied for missions in the past, planned or discussed.

All of these mission types consist of a number of phases and their individual characteristics concerning possible malfunctions.

Tab. 1:
NPS mission types

radio-isotope generator	mission type	nuclear reactor
	low earth orbit (short lifetime) and subsequent transfer to a parking orbit , cf. Fig.23	mission as carried out
mission as carried out	high earth orbit (lifetime longer than 300 y)	mission as carried out
	high earth orbit (lifetime longer than 300 y) and application for paiload transport to GEO (OTV)	discussed
mission as carried out	deep space without swing by at earth, cf. Fig.24	
planned	deep space including swing by at earth, cf. Fig.25	

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• Probability of malfunctions during an orbital manoeuvre

The transition from one mission phase to the following is attained with the aid of active orbit manoeuvres. Because failures can occur in this, these orbital manoeuvres represent a decisive factor in the discussion of safety aspects.

In order to be able to carry out a faultless orbit transfer manoeuvre, trouble-free functioning of at least the following five sub-systems is necessary:

- power supply
- thruster with starter
- temperature control system
- attitude control system
- board computer or communication system for issuing commands

Each of these sub-systems fulfills its function with an, albeit small, probability of failures. These failure probabilities depend on the design, the quality of the fabrication and the age. An empirical value for this kind of sub-systems may be a reliability of 98 %. If this presumption is then made for all five sub-systems, there results a failure probability for the entire orbit transfer system of 9.6 %.

In fig. 26 the entire failure probability of an orbit transfer system with five sub-systems is plotted versus the reliability of the individual systems. The statistical failure probabilities for launch and orbit transfer of any missions carried out so far are in the order of magnitude shown in fig. 26.

3.2 Missions with nuclear reactor on board

The consequences of malfunctions of manoeuvres during a mission with a nuclear reactor on board are discussed in the following under the presumptions that

- the premature criticality of the reactor is prevented under all circumstances (even in water)

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- the reactor is not used until the planned operational orbit is reached.

■ Failures on the ground

If a failure occurs during transportation to the launching pad, on the launching pad itself before the start or immediately at the start, then the national and international safety directives are relevant. With respect to the nuclear fuel masses used at present in satellite missions (approx. 50 kg/start) in comparison to those used in reactor plants on the ground (up to 100 tonnes), any international risk posed by the reactor on board a satellite in case of an accident at the launching pad will only have minor significance, especially if the reactor remains sub-critical.

■ Failures during the ascent phase

If a failure of the first or second rocket stage (total or partial failure, explosion etc.) occurs during the ascent, this leads, after a ballistic flight, to an impact of the entire equipment or of debris on a ground track known in advance, as a rule no further than 2500 km from the launching pad. In general this ground track is on water.

If one of several engines fails, there can be some deviation from this ground track as a result of the thrust vector deviation and resulting torques.

If corresponding safety arrangements have been made along this ground track (quick search and recovery of the object) and the reactor remains sub-critical even in water, a failure of the first or second rocket stage does not mean a significant radiological hazard to foreign territories.

■ Failures of the third rocket stage (upper stage)

If the third stage fails partly, the orbit reached can be too low. The result of this is an uncontrolled re-entry over any territory within the belt of latitude = ± inclination (cf. fig. 16).

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An uncontrolled re-entry is especially possible after only a few hours or after an incomplete orbit, practically without previous warning. Intact, re-entry, burning-up and / or mechanical destruction are possible.

Since the nuclear reactor has not been operated prior to this point in time, the radiological hazard posed by this event is limited (cf. previous chapter). Nevertheless, it is an international affair.

- Failures in the transfer from Low Earth Orbit (LEO) into a parking-orbit*

As described in chap. 3.1, the transfer from the LEO to the parking-orbit consists of two successive propulsion phases (cf. fig. 23).

If, in this planned transfer, the first thrust impulse fails, the object together with the reactor remains in the low initial orbit. The reactor was in operation up to this time and a fission product inventory was produced. The lifetime remaining on this orbit is stated in chap. 2.1.1.

When the second thrust impulse at the apogee of the transfer orbit fails, the object together with the reactor remains on this elliptical orbit. The corresponding lifetime can be obtained from chap. 2.1.1.

In the two cases described above, the nominal lifetime, which would be sufficiently long for the decay of the fission products, is not reached. This means that the re-entry occurs with a high radioactivity anywhere in the area inside the belt of latitude ± inclination (cf. fig. 16).

The re-entry behaviour which is now possible can strongly deviate from the one originally planned, this being the case when the planned separation of the satellite from the reactor and the separation of the nuclear fuel does not take place.

* Refer to chap. 5.2.1: Sufficient High Orbit

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In any case, both intact re-entry and also complete or partial burn-up and/or mechanical destruction of the object can bear a certain hazard due to the undecayed fission product inventory as discussed in chap. 4.2.

Besides these more probable cases of failure, also thrust vector deviations can occur in the first or second thrust impulse (e.g. failure of the attitude stabilization).

As shown in fig. 26, this leads in the most unfavourable case to an immediate re-entry. For this case, the above mentioned consequences are valid with the addition that practically no satisfactory time remains for precautionary measures on the ground.

An overview on missions with nuclear reactor on board (including their specific phases and possible malfunctions) is given in fig. A of chap. 1.

3.3 Missions with radio-isotope generators on board

When using radio-isotope generators there is a large inventory of radio-active substances from the very beginning of the mission. So, in the following considerations, it is always pre-supposed that a containment system is used.

- Failures on the ground

When deploying radio-isotope generators, the national and international regulations for the launch preperation and the failures possible on the launching pad are generally applicable as described for reactor deployment in chap. 3.2.

The difference from the nuclear reactor is however that the entire radio-activity is contained from the outset in the ready installed radio-isotope generator. The fact that this activity can never be switched off determines all the transportation, installation and other operations necessary in the start preparations. The containment must expecially be designed in such a way that it can withstand

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the largest imaginable explosions and fires of the booster rocket. The safety criteria to be applied here are however part of the national competence of the territory of the launching pad.

- Failures during the ascent phase

The orbit-mechanical consequences of a failure in the ascent are as described in chap. 3.2 for the reactor.

The radio-isotope battery would impact after a failure during the rocket ascent (first and second stage) on the ground track close to the launching site and known in advance, with a certain probability on the sea surface.

The containment system must be designed in such a way that it does not break up on impact under all circumstances. Clean-up operations must be performed immediately especially in the case of a containment break-up. This requires close tracking of the object during the last part of crash-down in order to determine the impact location very soon. Measures must be taken so that the radio-isotope generator can be traced and recovered in such a case.

Should it not be possible to recover the radio-isotope battery from deep sea water, then it must be guaranteed that a radiological/toxic polution is safely inhibited. In this respect, the resistance of the containment against sea water plays a decisive role.

- Failure during the operation of the upper stage of the rocket and re-entry conditions

A partial failure of the upper stage of the rocket can lead to manifold deviations from the nominal path. In so far as a complete earth orbit is not reached, the considerations of chap. 3.2 apply. If an earth orbit was reached, then two marginal cases can be identified from the large number of possible faulty courses:

a) A low-eccentricity orbit near the earth can be reached. After a short period in this orbit, there follows an uncontrolled re-entry to an area of the earth's surface which cannot be determined before-

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hand (inside the belt of latitude corresponding to the trajectory inclination, cf. fig. 16). The containment system must be designed as to survive the aerodynamic heating and the aerodynamic forces during the re-entry path. The isotopes, which are still encapsulated, impact on the ground or the sea surface and must be recovered from there. This requires close tracking of the object during the last orbits in order to determine the impact location as precise as possible. In case of submergence in deep sea water the same as in the last paragraph applies. The point of the impact can only be localized in the final re-entry phase (a few hours before the impact), cf. chap. 2.2.1.

The searching and recovering area will normally be in foreign territory, which generally means international action being necessary.

b) In a second marginal case, the earth escape trajectory is not reached completely on a planned deep space mission through partial failure of the upper stage of the rocket, with the result that the object with the radio-isotope battery remains in the earth's field of gravity on a highly eccentric ellipse with an eccentricity directly below 1. The lifetimes and special orbit mechanical circumstances listed in chap. 2.1.1 are valid for such highly eccentric trajectories. The re-entry behaviour of such trajectories is discussed in chap. 2.2.2.

It should, however, be pointed out that considerably higher temperatures result from re-entry from such highly eccentric trajectories and larger aerodynamic forces become effective. The containment system should be designed thermically and mechanically in such a way that it also covers this case. Bare plutonium-oxide would melt under these circumstances (cf. fig. 22).

- Failure during a swing-by manoeuvre at the earth

If the trajectory of a swing-by manoeuvre can not be reached as planned due to a malfunction, a subsequent re-entry of the radio-isotope generator can occur. The above mentioned aspects concerning a re-entry from a highly eccentric orbit apply, bearing in mind the thermal and mechanical stress still higher in this event.

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An overview on missions with radio-isotope generators on board (including their specific phases and possible malfunctions) is given in fig. B of chap. 1.

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4. RADIOLOGICAL HAZARD RESULTING FROM ACCIDENTAL RE-ENTRY OF NPS

4.1 Introduction

As we did not intend to study a distinct system and due to the lack of detailed design information for NPS we analized some general, postulated accidental scenarios and power sources concentrating on what we thought might be reasonable system data and scenarios or what might be scalable for comparison.

So in this chapter we present model-calculations for the radiological doses resulting from

- a nuclear reactor assuming
  - total dispersion of a reactor in form of aerosols
  - dispersion of a reactor in form of small particles
  - intact re-entry
  - the release of volatile nuclides from a reactor reentered compact and damaged during impact
- a RTG assuming
  - complete burn up in the stratosphere
  - compact re-entry of fuel-pellets

All these calculations postulate in principle the orbital decay of the system after an accident without discussing the probability of this accident.

In some cases we also had to make some additional assumptions or simplifications in our models. We however think that these results - taking into account these restrictions - inspite give a sensible assessment of the radiological hazard resulting from NPS in space in case of an accident.

It should be noted that this study is not comprehensive in that not all possible accident scenarios and accident locations could be evaluated by calculations because the respective data were not available and the evaluations would have been specific with respect to a special mission. Among those not considered are accidents possible at the launch pad, during transport, and some

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scenarios during re-entry, e.g. re-criticality. Because of the same reasons we also could not take into account special features of special systems (e.g. fragmentation of RTGs in case of explosions or activation products of reactors which increase the radioactive dose and in case cause a longterm hazard if long living products are present). In these cases a specific evaluation for each system would be necessary.

4.2 Nuclear reactor

4.2.1 Inventory and sourceterm of the nuclear reactor

As a bases for the calculation of the inventory of the reactor-systems we assumed two systems with 50 kW and 500 kW thermal power and 1 year and 10 years respectively for the time of operation. The inventory of the reactor to be applied for the calculation of the sourceterm and the resulting doses was calculated with the computer code ORIGEN2. The code was used to determine the contents and the radiological decay of fission products and actinides by assuming the thermal power (50 kW and 500 kW) and the time for the operation of the reactor (1y and 10y). We abstained from calculating the activation products because of lack of information about the alloys and masses used in a system. So it should be noted that the doses calculated do not consider contributions from activation products and so in some cases may underestimate the real doses. For the time being we assume that for early accidental orbital decay from space this contribution will be small compared to the contribution from fission products. This may not be true for the end of the mission after 300 years, if long lived activation products are present.

We should mention that in principle it is possible to scale the inventory with respect to the thermal power for equal times of operation, it is, however, not possible to scale the inventory with respect to the time of operation for constant reactor power.

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4.2.2 Hazard from a dispersed reactor

4.2.2.1 Dispersion in form of aerosols

To calculate the concentration of radio-active nuclides in the air near ground and the concentration deposited on the ground needed for the dose calculation in the first step we decided to apply a relatively simple box-model to calculate the transport in air. Such models have already been used to evaluate the atmospheric dispersion of nuclides resulting from weapon-tests. The results presented in this chapter are calculated using such a model. Fig. 27 shows two example-calculations of the transport from 40 km and 80 km height respectively. For in injection of $3.7*10^{13}$ particles (1000 Ci) the airborne concentration (particles/m^3, marked 'Air'), the deposition per year (particles/m^2/y, marked 'Grd dif') and the integrated deposition in (particles/m^2, marked 'Grd int') are plotted. Obviously it takes longer to transport the material from 80 km altitude down to the ground and so the yearly concentrations in the first years in this case are lower.

We decided to carry out additional calculations in a second step using the transport- and concentration data gained with a model able to consider also more complex atmospheric effects as large scale eddies in the lower stratosphere and troposphere. These effects may have an important influence because a quick mixing to the ground may be caused and seasonal effects can play a role. The intention is especially to review whether seasons and geographic regions might lead to transport effects resulting in an increase of doses. (The results will be distributed when the data of the transport calculations have been made available by a subcontractor).

For a standard input the calculation of the atmospheric transport gave us a standard concentration of particles in the air and on the ground as a function of time (cf. fig. 27). These concentrations were averaged over one year each. Multiplying this standard quantities with the actual activity of each nuclide corrected for radio-active decay and production of daughters for the actual time, we obtained the actual activity concentration in the air and on the

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ground for each nuclide for the time considered. These activity concentrations could be used as input data for the dose calculations.

To calculate the individual doses several exposure pathways had to be considered:

- the gamma-dose from the airborne concentration,
- the beta-dose to the skin from the airborne concentration,
- the dose resulting from the inhalation of radio-active material,
- the gamma-dose from the accumulated activity deposited on the ground taking into account the radio-active decay. A reduction from migration or other effects, e.g. shielding by the soil, was not taken into account;
- the dose resulting from ingestion of radio-active material.

The doses resulting from all fission products and actinides were calculated for several organs and for the effective dose using actual dose-conversion factors published by the Federal Health Office of the Federal Republic of Germany based on data published in ICRP 30.

Assuming a homogenous worldwide distribution as calculated by the box-modell, results are shown for the 50 kW system (1 year of operation) in fig. 28 for the effective dose (EffD) giving the contribution from the exposure pathways 'cloud' (Cld, gamma-dose from the air), 'ground' (Grd, gamma dose from the ground), 'inhalation' (Inh) and 'ingestion' (Ing). The doses are shown as yearly doses (mSv/y, marked as '_D') and as integrated doses (marked as '_I'). In fig. 29 the sum of a exposure pathways for the effective dose and the organ doses for bone marrow (BnM), lung (Lun) and bone-surface (BnS) are also presented as yearly doses and integrated doses. For the bone surface the exposure from the ground was not calculated. This is the reason why this curve does not bend up after 10 to 20 years but follows the decay of the airborne concentration.

The doses for the reactor system under consideration are in the range of 1e-6 mSv in the first years. The total doses after 50 to 70 years reach 1e-5 mSv. It is obvious that the gamma dose from the ground represents the main long-term contribution. The respective

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doses for the 500 kW-system are by factor 50-100 higher than these doses. The factor depends to a degree on the organ and the exposure pathway.

The figures show that the resulting doses calculated for homogenous dispersion of a system in the northern hemisphere (resulting also in a smaller individual dose in the southern hemisphere) give quite small doses to the individual under the assumptions discussed above. These doses are far below the natural background from external exposure e.g. from cosmic rays. In spite a collective dose might be calculated which is not so small because the material is uniformly distributed all over the world. Under the conditions discussed these doses might be scaled with respect to the number of events and the reactor inventory.

It should be stressed, that this results may change significantly when applying a more sophisticated model for the atmospheric transport and looking at doses applied for the first year(s).

As discussed by IfRR in chap. 2.2.2, the complete dispersion in form of aerosols my not be possible e.g. for UO2-material, as the melting temperature is not reached during orbital decay. This means that a total dispersion in this form most probably will not occur unless provided for by special design characteristics or a different reactor fuel.

4.2.2.2 Dispersion in form of small fragments

To calculate the resulting doses from small particles the inventory of the 'small' reactor system (50 kW, 1y operation) was used. For this system the resulting dose rates of the non volatile fission products were calculated for several decay times as a function of distance for a particle with a 'standard diameter' of 0.2 mm including absorption in air, but neglecting self-absorption in the material. For the further calculations we assumed that the dose rate of particles with diameters less than 1 mm diameter which are assumed for the calculation should be scalable with respect to the mass.

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The particles in the scenario discussed would be deposited in an area determined by the flight path and the wind direction with the aerodynamic diameter being the most important parameter. Though this scenario corresponds to the experiences gained in Canada after Cosmos 954, details for a more detailed analysis are lacking and had to be replaced by assumptions or parameter modifications: number, distribution, particle size and activity of the particles depend strongly on the reactor characteristics and the accident scenario. As the distribution over the area and the distribution of the particle diameters was not known, we decided to choose a model area with a random local distribution of particles. The diameters of the particles distributed were also determined randomly assuming a uniform distribution of all diameters considered. In practice this means that particles with different diameters were not seperated by the wind (zero wind speed). For this distribution the doses accumulated in one year and for 1 m distance from the ground could be calculated. Fig. 30 displays the dose in the first year in 1 m height resulting from 400 particles of 60-900 µm diameter randomly distributed in a 2*2 km^2 plane if a person would stay at the respective place for one year. The curves present the respective doses for cuts in the plane assuming y=const for each curve. The hypothetical values may reach some mSv in a year near a particle.

To obtain more realistic individual doses resulting from these particles in the population we tried to simulate roughly the behavour of persons in this area by

- choosing a point randomly defining the 'residence' of a person. For this point the dose was calculated for a year with the person 'living' there 12 hours per day.
- randomly determining 4 points for the remaining time of each day of the year where the person is staying 3 hours per point.

The decay of the fission products in this year was considered in 5 steps.

This model allows a rough estimate of the doses applied to persons assuming different conditions and particle diameters. Some results are shown for different conditions in the figs. 31 and 32. Fig. 31 gives the doses of 60 persons in the first year for 400 particles sized 60 µm to 900 µm in diameter in an area of 2*2 km^2. Most of

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the doses are far below 0.1 mSv, the dispersed particles in this scenario may result in individual doses in the mSv-region, if counter measures are not taken into account.

Fig. 32 shows the results of two calculations assuming a fixed particle diameter of 900 µm and 200 µm respectively for 400 particles in the plane. These calculations may demonstrate the tendency resulting if a separation of particle diameters by the wind takes place. It should be mentioned that the number of persons in the calculation probably is too low to show single events of high doses as could be found in fig. 31.

It should be mentioned that there may be special scenarios resulting in even higher individual doses than those calculated under these assumptions. For instance a very close or direct contact with even very small particles may result in quite high local doses causing e.g. skin burns. For a range of particle diameters up to some 100 µm diameter (especially particles not contributing to inhalation, and not easily detectable and recovered) ingestion of these particles may occur resulting in organ doses. This effect was not evaluated, but may necessitate control of food consumption. To reduce the hazard resulting from such special scenarios the detection and collection of particles at least in special places may be necessary, however, detection and location of these particles is difficult because of the large areas (possibly ten thousands of squarekilometers) to be screened and the dose rates being in the lower ranges of the dose rate meters. For the small particles discussed here surveys by helicopter probably will be very difficult, if not useless.

4.2.3 Hazard from compact re-entry

Assuming the compact re-entry of a reactor core the scenario of the impact may differ: it may fall into the sea, in case of an impact on soil the core may be buried and shielded by the soil. In case of an impact on a hard surface this may be not true, additionally some damage may occur to the core.

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4.2.3.1 Direct Radiation from the Intact Core

Postulating an impact on a hard surface for a nuclear reactor with a power of 50 kW and 1 year operation the dose rates as a function of decay time and distance were calculated. The inventory calculated with ORIGEN2 was used as a basis for the estimation of the dose rate of a compact reactor reentering intact without shielding. As details of the design could not be taken into consideration we assumed a cube of uranium to take self-absorption into consideration. As this is only a crude assumption, the dose rate determined may include quite large errors. We think this to be acceptable when only the range of dose rate is taken for the discussion.

Activation products were not considered. This in principle underestimates the dose rates.

As we wanted to obtain an upper judgement of the hazard, we postulated short or negligible decay times for the reactor without to consider the probability of such a scenario.

The check for dose rates resulting in doses higher than e.g. the dose levels discussed in ICRP 40 and effording counter measures included the evaluation of the efficiency of shielding the reactor by standard materials. This was done by assuming concrete walls of different thicknesses.

The results of these calculations are summarized in fig. 33. It shows the dose rate from a compact reactor of 50 kW and one year operation in mSv/h as a function of distance and time after shut down. In 5 m distance a 10 cm concrete wall is assumed, which may be taken as the wall of a house. The doses may be in the following range:

- zero decay time
  100 Sv/h in 1 m distance,
  2 Sv/h in 10 m distance,

- 1 day decay time
  10 Sv/h in 1 m distance,
  200 mSv/h in 10 m distance,

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- 1 year decay time
  2 Sv/h in 1 m distance,
  40 mSv/h in 10 m distance.

It is shown that for short decay times and small distances lethal doses are reached in a short time and that shielding of e.g. houses is not very effective. The dose rate data may be scaled with respect to the power of the reactor and in case additionally are increased by a higher operation time.

Fig. 33 in its second graph also demonstrates the effect of shielding for the same reactor for 0 and 1 day radio-active decay and a concrete wall of 10 cm, 50 cm and 100 cm in 5 m distance from the reactor (No shielding up to 5 m). The shielding factors for concrete in this situation may be

- a factor of 5 for 10 cm concrete,
- a factor of 100 for 50 cm concrete,
- a factor of 104 for 100 cm concrete.

Looking at the dose rates for these scenarios, it is obvious that emergency measures have to be taken to protect the public if the reactor comes down in a populated area. Early fatalities might be caused after a short time without protection. Dose levels dicussed by ICRP 40 for evacuation might be reached up to distances of 100 m to 1000 m for the system discussed.

The recovery of the system may not be easy because of high local dose rates and lack of tools, shieldings and transport systems.

4.2.3.2 Volatile fission products from a damaged core

In case of an impact on very hard surfaces the reactor system may be damaged and volatile fission products may be released. In this case long-term-effects as well as short-term exposures have to be considered.

The source term to be applied also was calculated with ORIGEN2 for the large system (500 kW, 10 years operation). The most proble-

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matic point is the estimation of the release from the fuel into the gap and from the gap into the air. As no real data were available for a space reactor, we decided to apply data used for the calculation of the release from fuel elements of a pressurized water reactor. The release factors applied to estimate the release from the fuel into the air are e.g.:

- Noble gases 8.0 %
- Cesium 0.13 %
- Iodine 0.075 %
- Tellurium 0.01 %
- Strontium 0.0001 %.

■ Long-Term Exposure

To estimate the doses from all volatile fission products released we used the standard model to be applied in the German authorization procedure for the calculation of doses resulting from incidents of nuclear power reactors. The meteorological conditions are 1 m/s windspeed, weather category C and 5 mm/h rain. The main exposure pathways are included and doses are calculated for up to 50 years after a release. The only exemption is for the ingestion-pathway: for a distance up to 2 km ingestion is only taken into account for the first day after the release. Beyond 2 km distance ingestion is included. (This is why the curves in the following figures show an irregularity between 1 and 2 km: there should be a step at 2 km indicating the additional dose from ingestion in the next 50 years and giving an impression of the countermeasure, however the plot routine is not able to show this step).

Fig. 34 shows the results of this calculation with long integration time of 50 years. The effective dose in Sv is presented as a function of distance for the exposure pathways and as the total dose (sum) for the time immediately after shut down and the 'large' reactor system. For this long integration times the doses mainly result from the exposure from the ground and from ingestion of radionuclides, as long living nuclides are mainly contributing. This also has the effect that the dose decreases only very little if radiological decay times up to some years are considered.

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The doses for 50 years exposure are calculated under the quite conservative assumptions, that the individual stays at the same place and consumes the food produced at the same place for 50 years. Normally these assumptions are made to assure conservative results in the licensing procedure for nuclear power plants in the Federal Republic of Germany. However, these doses might be compared to the respective design level of 50 mSv for incidents. Obviously the doses in this scenario are far above this level.

- Acute Short-Term Exposure

To check whether dose levels relevant for emergency measures are reached we did some additional calculations using the same scheme but different integration times for the exposure from the ground and for the resulting dose from inhalation. In the F.R.G. doses to be weighted against reference levels for emergency measures have to be integrated over 7 days without using reduction factors and thus arriving at a potential dose for a person. Ingestion is not included in this comparison as it is assumed that this pathway can be avoided by counter measures. The results are presented in figs. 35 to 37. Fig. 37 additionally shows an estimation for the dose recieved from the deposited nuclides in one year. This dose may be taken as a reference for the relocation of the public. The doses for one year were extrapolated by multiplying the 7 days' doses by a factor of 50. This will give an acceptable approximation if mainly nuclides with long half-lives are contributing, which is the case after 1 to 10 years.

For the worst case condition the results show that levels for acute countermeasures are not reached in this case for the distances shown. The short-term data are strongly dependent on the decay time, so the short-term doses decrease rather quickly with time in the first days and months. (factor of appr. 10 in the first year). Looking, however, at fig. 37, the dose for one year (after 10 years decay!) shows that longterm measures as relocation or decontamination might be necessary in an area around the reactor downwind, if a system reenters shortly after shut down. In summary the calculations show that the volatile fission products would pose less hazard than the direct radiation from the core.

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It may however be taken from fig. 34 that ingestion is an important contributor to the dose and so foodbans or at least control of food produced in that region will be necessary.

4.2.4 Summary Concerning the Hazard of an Accidentally Reentering Nuclear Reactor

- Complete dispersion in form of earosols

Resulting individual doses are quite small, if the reactor is small and the probability of this scenario with respect to the number of operating reactors is small. (Though collective doses might be relative high)

The possibility of the complete transfer of the reactor core into aerosols as assumed, however, is questionable.

- Dispersion in form of small particles

Dispersion of small particles will be limited to a possibly very large, but limited area (depending on the winddirection and particle size areas of some 10.000 km^2 may be possible). The individual doses for most of the exposed persons will be small, but under special conditions doses of mSv or high local organ doses may occur. Precautionary countermeasures for the ingestion pathway may be recommended to avoid ingestion of particles in the size range of some tens of µm.

Countermeasures with respect to detection and recovery of particles are difficult and costly.

- Early accidental compact re-entry

In case of an early fast accidental re-entry without a decay of the radioactivity and without counter measures, doses leading to early fatalities or high doses resulting in a high cancer risk may occur within some hundred meters around the reactor in a short time. In addition the impact of a compact reactor causes a high conventional risk. In any case protection measures probably will be difficult.

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If volatile fission products are released after the impact the acute hazard may be small but long-term counter measures may be necessary in the area downwind.

In case of an accidental compact re-entry burial of the system in soil or in the sea may - theoretically - be less hazardous than the scenarios discussed here, but in case of an uncontrolled re-entry the impact into a populated area (containing many hard surfaces) or on rock cannot be excluded.

4.3 Radiological hazard resulting from RTG

After the burn-up of an RTG in the sixties the principle design of these systems has been changed. New improved design with a protection against dispersion is state of the art, but some devices designed for dispersion are still in space. For RTG's of the new design, in case of an accidental decay a dispersion in form of aerosols is not probable if the RTG is not damaged by an explosion. But damage by impact on rock might be not impossible. This may result in a local contamination. From this side of view our assumptions of dispersion only hold for some older systems stil in space. As, however, the results to be presented are normalized to $3.7*10^{10}$ Bq (1 Ci) of Pu 238, they may also be applied to scenarios with partial dispersion in form of aerosols. It has, however, to be kept in mind that the distribution of the diameters of the aerosols or small particles formed in this case are not considered and that for the calculation the aerosols are assumed to be available for inhalation.

The steps carried out for these calculation are summarized as they are mainly similar to those described in chapter 4.2.1 and 4.2.2.1 (the calculation of the doses resulting from the dispersed reactor core).

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4.3.1 Sourceterm

The inventory with time was calculated starting with pure Pu 238 using the ORIGEN2-code. So the resulting decay products could be determined as a function of time. It should be mentioned that in this case long lived daughter products are formed, some of which decay by high-energy gamma-rays.

4.3.2 Dispersion in form of aerosols

The inventory was taken as totally dispersed as an aerosol available for inhalation. This most probably is a conservative assumption. The time of operation was taken as zero for the calculations shown later. This assumes a 'new' RTG at the beginning of an operation. The source term was taken as a standard of $3.7*10^{10}$ Bq giving a standard dose to be scaled by the actual inventory.

The transport was also modelled with the box-model as applied for the reactor. The doses shown were calculated for a release hight of 40 km.

As Plutonium especially contributes to the doses of some organs (bone and lung) these organ doses were calculated for this scenario.

The figs. 38 to 40 present the contributions of the exposure pathways to the effective dose and the organ doses for the bone marrow, bone surface and lung as yearly doses and as integrated doses (for abbreviations refer to chap. 4.2.2.1). Fig. 40 shows the total doses summed over the pathways. It must be mentioned that the doses calculated for the bone surface do not contain the external doses from the cloud and from the ground. This is why these curves do not bend for longer times as the other curves do when the doses from the airborne concentration decrease and the dose from the ground (resulting from the deposited activity still producing daughters which decay by x-ray and gammas) is the dominant pathway. Obviously the inhalation and the ingestion are the main contributors to the doses in the first time, whereas the

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dose from the ground is quite neglegible. As can be taken from fig. 40 the bone surface in this case is the most exposed organ, whereas the effective dose is low, because the most exposed organ only contributes little to the effective dose and gamma-ray do not contribute to the exposure in an amount worth mentioning.

The doses resulting from the scenario discussed strongly depend on the inventory of the RTG. Assuming a homogenious distribution by a box-model, the effective dose is relatively low. Organ doses with accumulation of plutonium are quite high. The organ doses for $3.7*10^{10}$ Bq (1Ci) Pu 238 are in the same order or only slightly lower than the doses calculated for the small reactor system though the contributions of the pathes and the organ doses may differ. With respect to the real inventory of a RTG these doses may be increased by orders of magnitude. The results shown may be scaled with respect to the inventory of a RTG.

4.3.3 Hazard from compact re-entry

Pu 238 as an alpha-emitter has only a very low probability for the emission of high-energy gamma-rays. Some daughter products of Pu 238, however, will decay by gamma-emission. This contributes to a flux of gamma ray of different energies. Though the contents of Pu 238 will decrease slowly with time, this flux will even increase after some time as the radio-active daughters will accumulate until formation and decay come into equilibrium. As some daughter have halflifes which are much longer than the halflife of Pu 238, the dose rate from gamma rays after a long time will be higher than that at the beginning. The time-dependance is shown in fig. 41. Additionally it should be mentioned that Pu 238 also emitts neutrons.

As discussed above modern RTGs (e.g. General purpose heat source, GPHS) are designed to reenter intact if the carbon heat shield surrounding the fuel pellets is not damaged. The dose rate of one single GPHS-pellet was calculated applying the some model as used to determine the dose rate of the compact reactor. One pellet consists of fuel enriched to 85 % of Pu 238. As the contents of other

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nuclides was not known, only the contents of Pu 238 was considered for the calculation. This may underestimate the dose rate. The dose rates were calculated for several time steps taking into account the formation of daughters with time. As may be taken from fig. 42 the dose rate of a pellet first decreases very slowly with time and will increase after some hundred years because of the effects discussed above. A comparison with fig. 41 may show that it will increase over the initial values after long times. As these pellets are quite small and the carbon shield (which will contain 4 pellets) does not represent an efficient shielding of the system, unconcious handling of and even more close contact with single parts of a RTG may result in organ doses and individual doses because of their small size. This may be an important point to be considered if RTGs should be operated in earth orbits and should be not retrieved after operation.

4.3.4 Summary

The calculations have shown that the dispersion of Pu 238 considering the inventory of radio-isotope generators may lead to quite high organ doses especially for organs accumulating plutonium. These doses by far may be higher than doses from small nuclear reactors. For new designed radio-isotope generators a dispersion is possible only under special accidental conditions. They probably will reenter intact under accidental conditions. As on one hand these generators might in special conditions, e.g. impact on rock, may be mechanically damaged, on the other hand even in case of Pu 238 the fuel may pose a hazard by gamma radiation also after long radiological decay times, the retrieval and recovery of radio-isotope generators after re-entry or directly from earth orbit is necessary to avoid dispersion, direct contact with and incorporation of plutonium and the unconcious handling of fuel pellets not recognized.

In case of retrieval on earth it has to be kept in mind that special systems may be necessary, e.g. sensitive radiation monitors or perhaps infrared sensing systems, as the rate of the gamma rays resulting may be low and will make surveys e.g. by helicopter difficult.

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5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

5.1.1 Launch and ascend phase, orbital manoeuvres

- Failures prior to or at launch are local events within the competence of the launching state

- Failures during the ascent phase (e.g. 1st and 2nd rocket stages) have effects only on the predetermined subtrack adjacent to the launching site if

  - nuclear reactors are safe against criticality under all circumstances (including impact on land or into water and submersion in water),

  - radio-isotope generators are protected in a containment system which assures that no radio-active material is set free.

- Failures of injecting a space object with NPS into earth orbit may lead to re-entry randomly distributed in the latitude belt corresponding to the orbit inclination, with very short pre-warning time (in worst cases only minutes before re-entry).

- Failures of injecting a space object with NPS into inter-planetary trajectories may lead to re-entries from highly elliptical orbits (HEO), with especially severe temperature and load conditions.

- Failures of a swing-by manoeuvre at the earth during an inter-planetary mission can lead to re-entries from hyperbolic trajectories with even higher thermal and mechanical load conditions.

- Failures of the transfer of NPS from LEO to a sufficiently high orbit (SHO) as defined in chap. 5.1.2, according to present technology and to the number of subsystems involved in this manoeuvre, can occur with a probability that is not sufficiently low. This failure rate can be minimized e.g. by the

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use of redundancies of subsystems. This failure leads to early re-entry randomly distributed in the latitude belt corresponding to the orbit inclination. Pre-warning is limited by the uncertainty of the re-entry time prediction which may be in some cases up to 10 % of the remaining life time and by the very limited possibility of predicting the re-entry location.

5.1.2 Operation and storage in sufficient high orbit (SHO)

- Operation of nuclear reactors in SHO from the beginning or storage of nuclear reactors in SHO after the end of the operation after a successfull transfer manoeuvre is comparatively safe, if the SHO assures an orbital life time sufficient to allow the radio-active fission- and activation products to decay to the initial level of the fuel. Further it is required that highly enriched U 235 is used as fuel in order to minimize Pu breeding.

- The altitude of the SHO must account for the possibility that during the long life time a destructive collision with space debris occurs. The probability for this is not negligible and may increase in the future. The altitude of the SHO should be high enough so that the radio-activity of the fragments produced in a destructive collision can decay to sufficiently low levels until re-entry.

- The operation or storage of Pu-fuelled isotope generators in high earth orbits would, even after very long times, lead to the re-entry of a still radioactive source followed by an intact impact or break-up on impact. In both cases this could not be accepted without provisions for tracking, and if required search and retrieval or clean-up. However, the organizational conditions for such activities may not be available in future centuries.

5.1.3 Re-entry and radiological consequences

- For the re-entry of nuclear reactors, which can be
  - the result of a failure during orbital operations

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- the normal procedure after the orbital life time on a SHO

potentially there are potential alternatives for the reactor design so that the nuclear fuel is

1) either completely dispersed in the high atmosphere in the form of aerosols
2) or dispersed in very small particles (sub-millimeter-region) in the high atmosphere
3) or is contained in a re-entry resisting containment leading to an intact impact.

In case of an early re-entry shortly after the end of the nuclear reactor operation, methods 1 and 2 both lead to individual doses from inhalation, ingestion and whole body radiation well below tolerable limits, although in case of method 2 for some individuals high organ doses may occur and countermeasuresmay be necessary to minimize the exposure. Method 1 though resulting in a contamination of the earth's surface might be preferable to method 2 which contaminates a large, but limited area. Method 1, however, may require a special form of fuel.

For both methods collective doses may become relatively high and for that reason the number of events should be limited in case of method 1 to avoid a world wide accumulation of radioactive material. The radioactive inventory of the reactor (a function of reactor power and time of operation) should be limited for both methods to reduce the amount of radioactive material dispersed.

Method 3 can lead to lethal doses for persons in the near vicinity of the impact and will require countermeasures in a short time. As an example evacuation may be necessary within some 100 m. Long-term contamination after break-up of the containment on impact may result from volatile fission products. Therefor it should be taken care that an accidental uncontrolled intact re-entry of a nuclear reactor into a populated area should be extremely improbable. In any case an early and detailed information concerning the orbital decay is highly necessary to be able to prepare countermeasures.

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5.2 Technical recommendations

5.2.1 Nuclear reactors

Nuclear reactors

- should only use highly enriched u 235 as fuel. The design should consider the radiological decay necessary for fission- and activation products.

- should assure by design and construction that the reactor cannot become critical before reaching the operating orbit, during all possible events as rocket-explosions, re-entry, impact on ground or water, submersion in water.

- are acceptable in operation on earth orbits
  - preferable on sufficiently h gh orbits (SHO), which means that the orbital life time is long enough to allow for a sufficient decay of the radioactivity to about the level of the nuclear fuel (actinides) itself;
  - on LEO with a subsequent transfer to SHO after the end of operation. The failure rate of the transfer should be minimized by reduncencies of subsystems.

  The altitude of the SHO should be chosen so that after a potential destructive collision with space debris the collision fragments also have long enough orbital life times.

- can be operated on interplanetary missions.

- should not be made critical before they have reached their operating orbit or interplanetary trajectory.

- should assure by design and construction that the risk to the population resulting from re-entry - either oprational or accidental - should be minimized. When judging this risk radiological hazard as well as conventional hazards should be taken into account

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5.2.2 Isotope generators

In view of the fact that isotope generators of the present design keep or even increase their radiological hazard over a very long time, it is recommended that isotope generators

- can be used for interplanetary missions and other missions leaving the gravity field of the earth. Isotope generators may be used for missions on earth orbits if they are retrieved to the earth's surface in a controlled way after the end of the mission.

- re-entries into the earth's atmosphere, which can occur after a malfunction in orbital operations, require an organization capable for tracking the re-entry and, on request, for search, retrieval or clean-up operations.

- shall be protected by a containment system, which withstands the heat and aerodynamic forces during the re-entry in the higher atmosphere under all possible orbital conditions, i.e. also from highly elliptical or hyperbolic orbits if relevant. On impact on the ground, the containment system and the physical form of the isotope shall assure that no radioactive material is introduced (in soluable, volatile, aerosol or microparticle form) into the environment, so that the impact area can be completely cleaned up from radio-activity by a retrieval operation.

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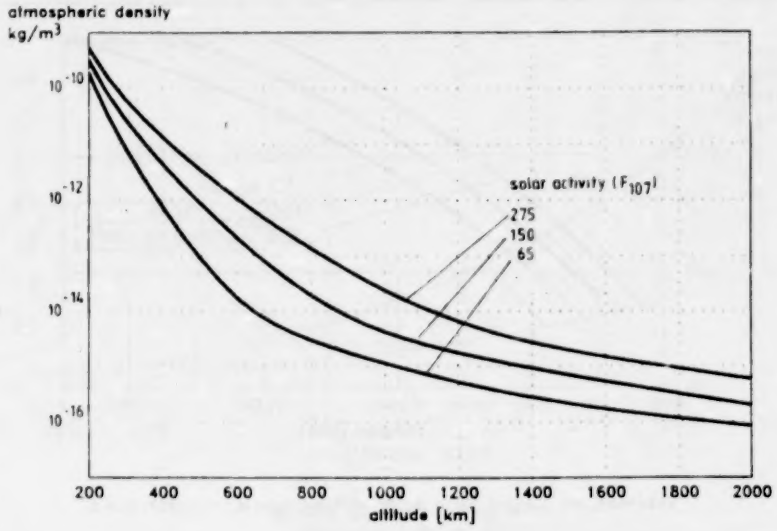
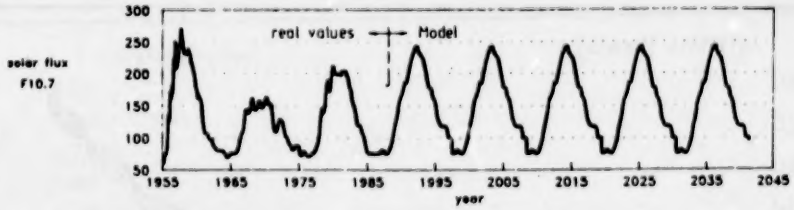
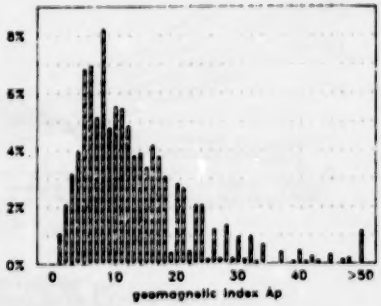


IFRR TUBS — ATMOSPHERIC DENSITY (MSIS)
averaged over daytime and season, geom. ind. Ap=14 — Fig.1



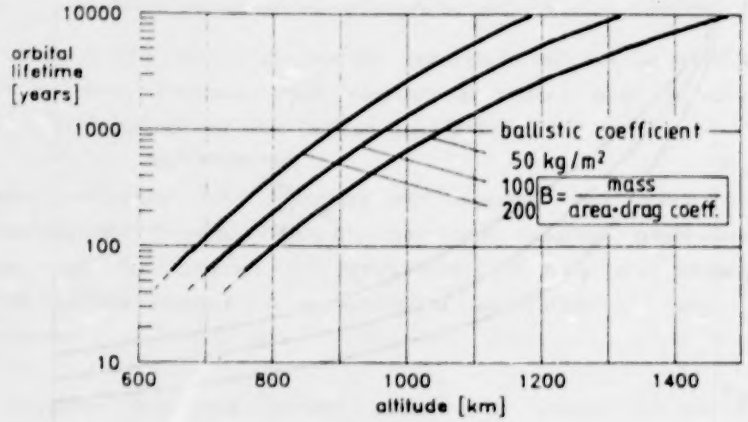
SOLAR FLUX MODEL FOR THE FUTURE
(WORST CASE)



GEOMAGNETIC INDEX Ap
PROBABILITY DISTRIBUTION
(FROM A 10-YEAR ANALYSIS)

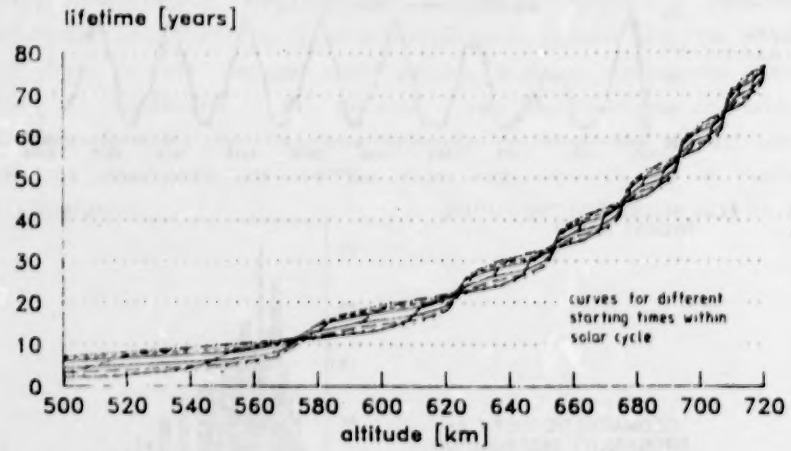
IFRR TUBS — LONG TERM INFLUENCES ON THE ATMOSPHERIC DENSITY — Fig.2

/...



assumptions : worst case solar activity model, circular orbits

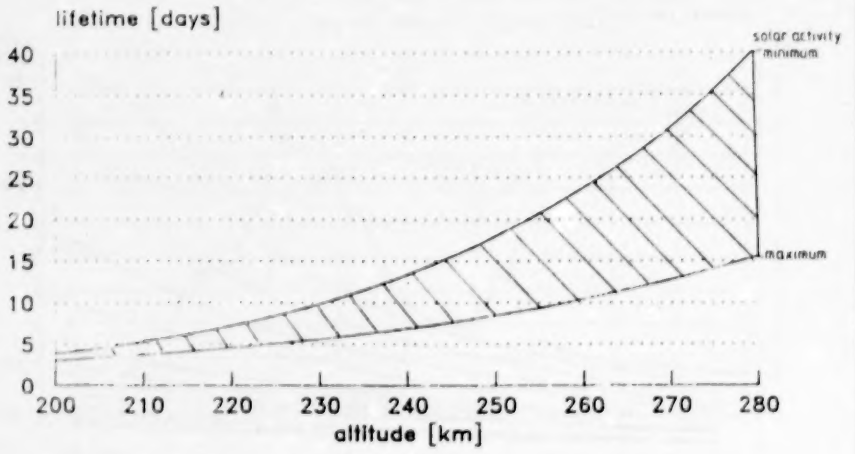
IRR TUBS | ORBITAL LIFETIMES (LOWER LIMITS) due to atmospheric drag | Fig.3



ballistic coefficient 100 kg/m**2
assumptions : worst case solar activity model, circular orbits

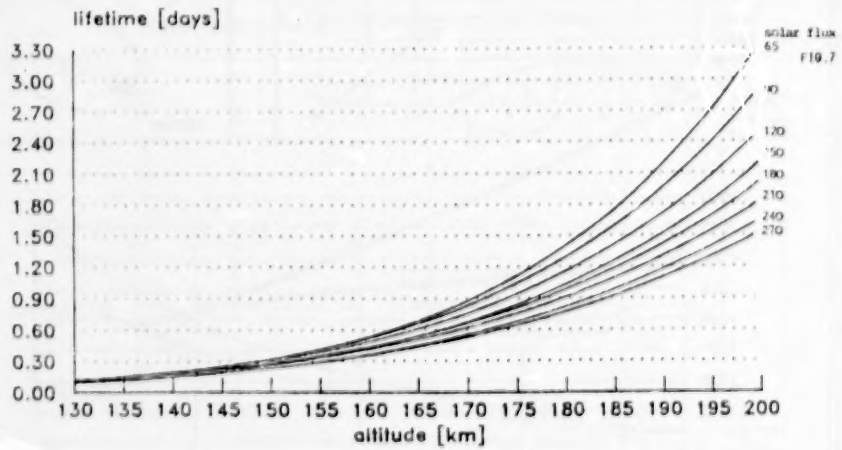
IRR TUBS | ORBITAL LIFETIMES AS FUNCTION OF SOLAR CYCLE PHASES due to atmospheric drag | Fig.4

/...



ballistic coefficient 100 kg/m**2
assumption : circular orbits
lifetime proportional to ballistic coefficient

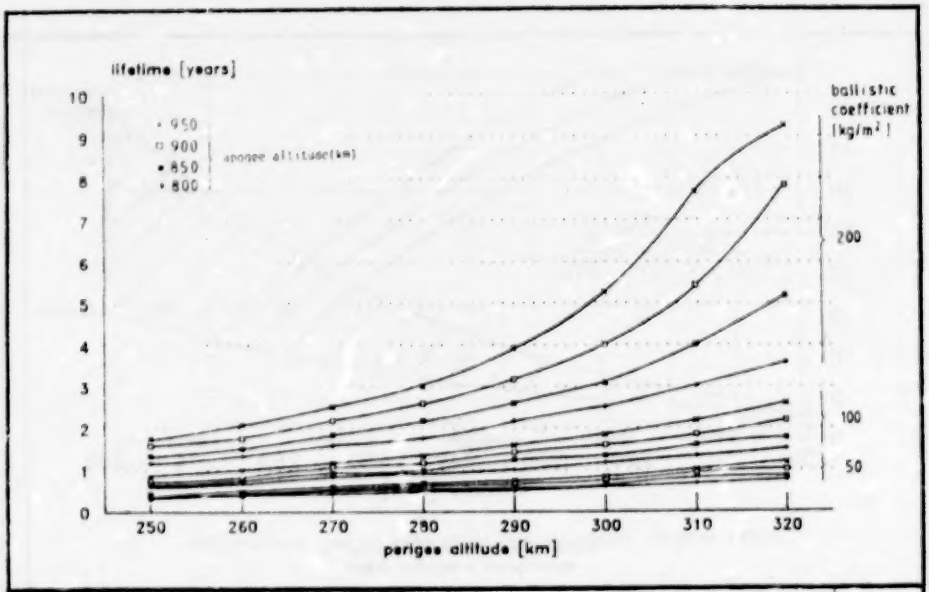
IIRR TUBS	ORBITAL LIFETIMES AS FUNCTION OF SOLAR ACTIVITY due to atmospheric drag	Fig.5



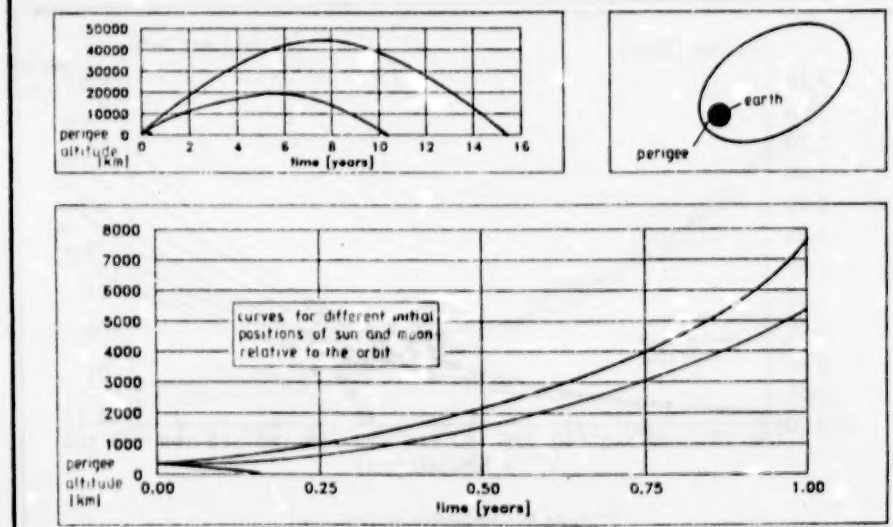
ballistic coefficient 100 kg/m**2
assumption : circular orbits
lifetime proportional to ballistic coefficient

IIRR TUBS	ORBITAL LIFETIMES AS FUNCTION OF SOLAR ACTIVITY due to atmospheric drag	Fig.6

/...

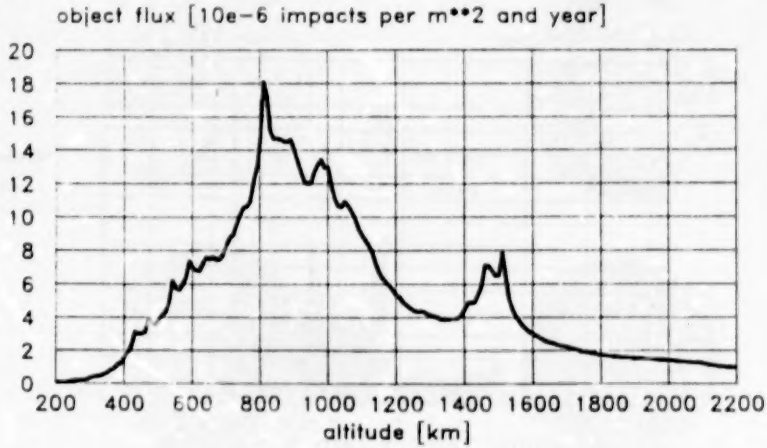


IHR TUBS	LIFETIME ON TRANSFER ORBITS worst case solar flux model, launched during solar maximum	Fig.7

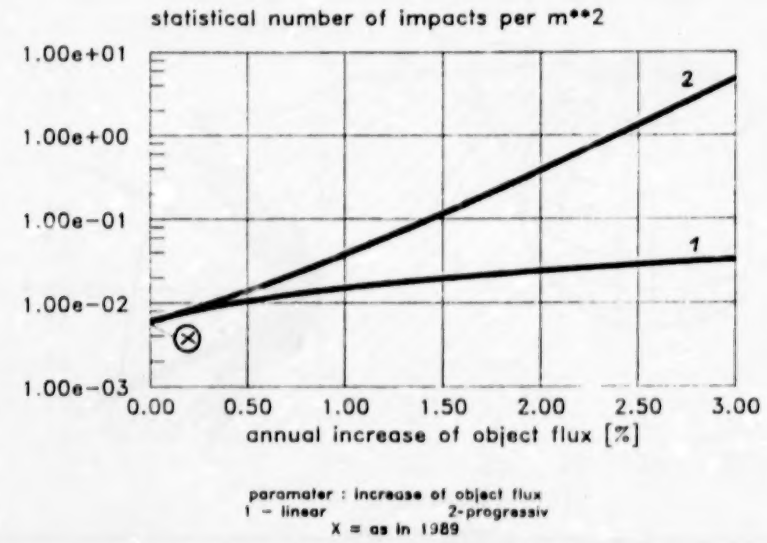


IHR TUBS	THE PERIGEE HEIGHT OF HIGH-EXCENTRICITY ORBITS due to lunisolar pertubations (example)	Fig.8

/...

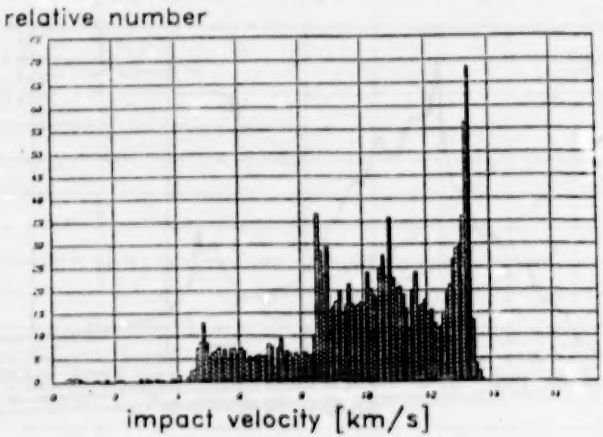


IIRR TUBS	THE CURRENT OBJECT FLUX (COLLISION RISK) ON EARTH ORBITS DUE TO OBJECTS LARGER THAN 1 CM	Fig.9



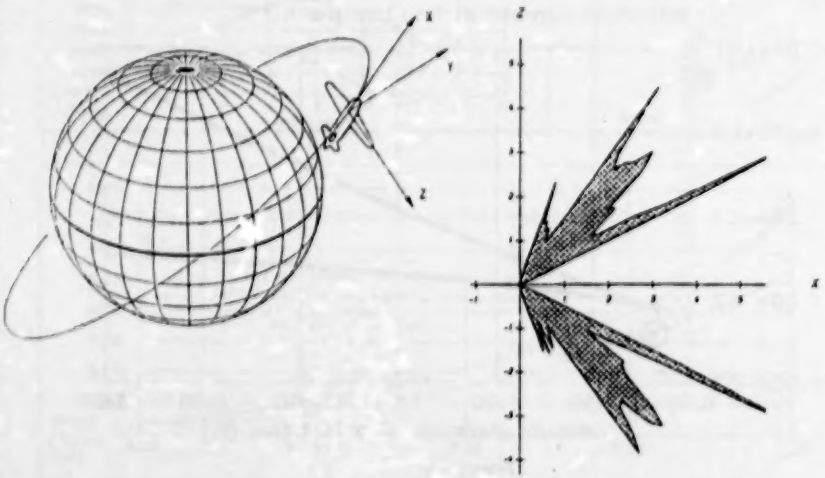
IIRR TUBS	NUMBER OF SPACE DEBRIS IMPACTS ON A SPACECARFT SURFACE AT AN ALTITUDE OF 1000 KM WITHIN 300 YEARS	Fig.10

/...



altitude 900 km
inclination 65 deg

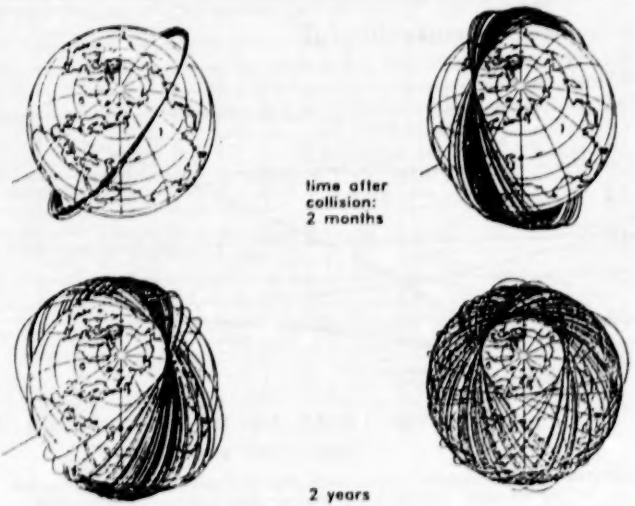
IRR TUBS	RELATIVE DISTRIBUTION OF THE IMPACT VELOCITY	Fig.11



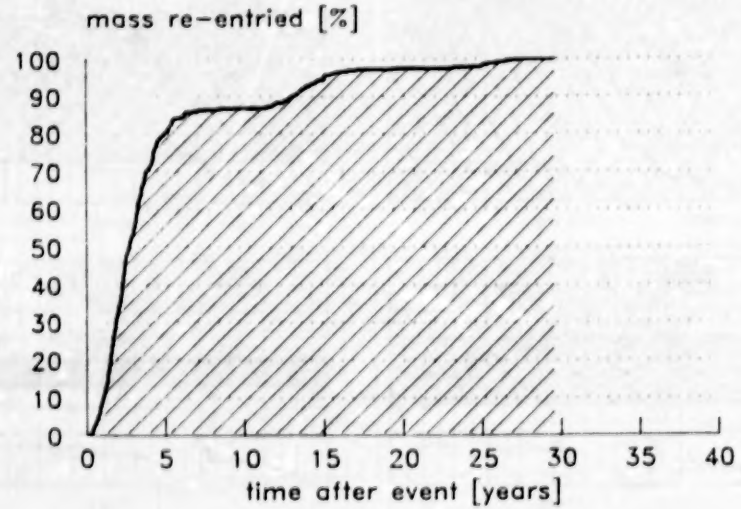
altitude 900 km
inclination 65 deg

IRR TUBS	IMPACT FLUX ANGULAR DISTRIBUTION	Fig.12

/...

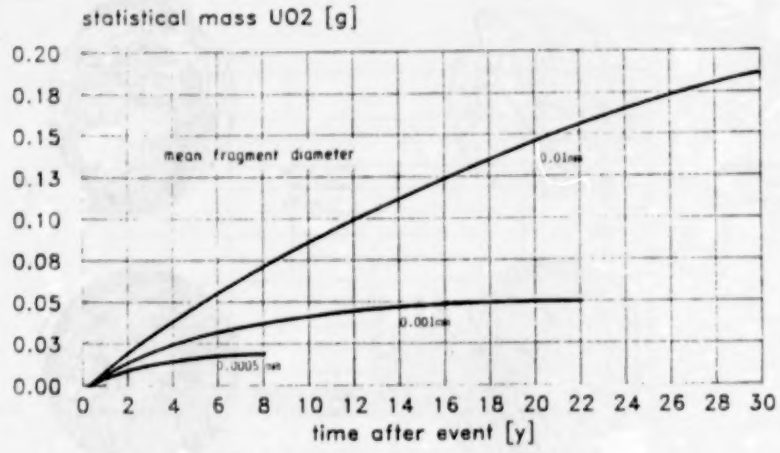


IRR TUBS	ORBITAL FRAGMENT DISTRIBUTION AFTER NPS COLLISION WITH DEBRIS PARTICLE	Fig.13



IRR TUBS	MASS RE-ENTRY AFTER A SIMULATED COLLISION (900KM ORBIT) particle diameter 0.01-0.1[mm], material UO2	Fig.14

/...

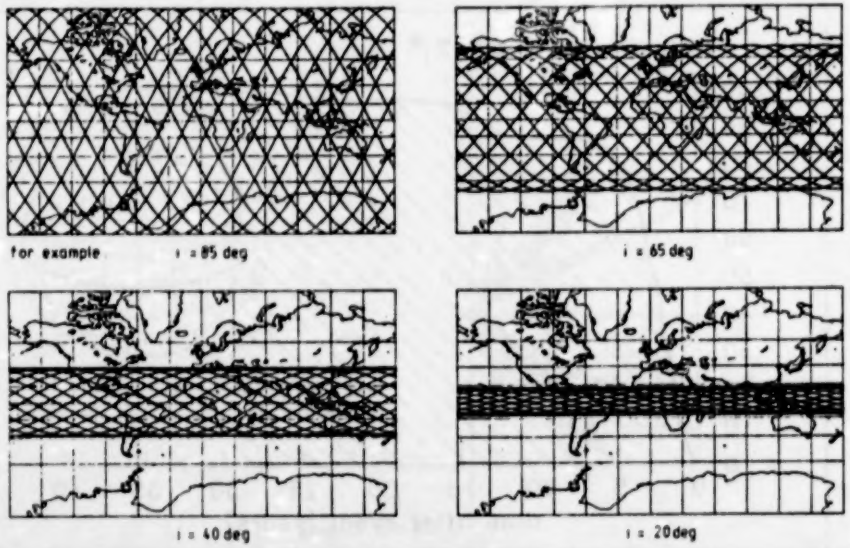


initial material : 50 kg UO2
fragments generated by a collision occured at 1000 km
station altitude : 500 km cross section of station : 1000 m**2

IRR TUBS

UO2-MASS ACCUMULATED ON THE SURFACE OF A SPACE STATION AS FUNCTION OF TIME

Fig.15

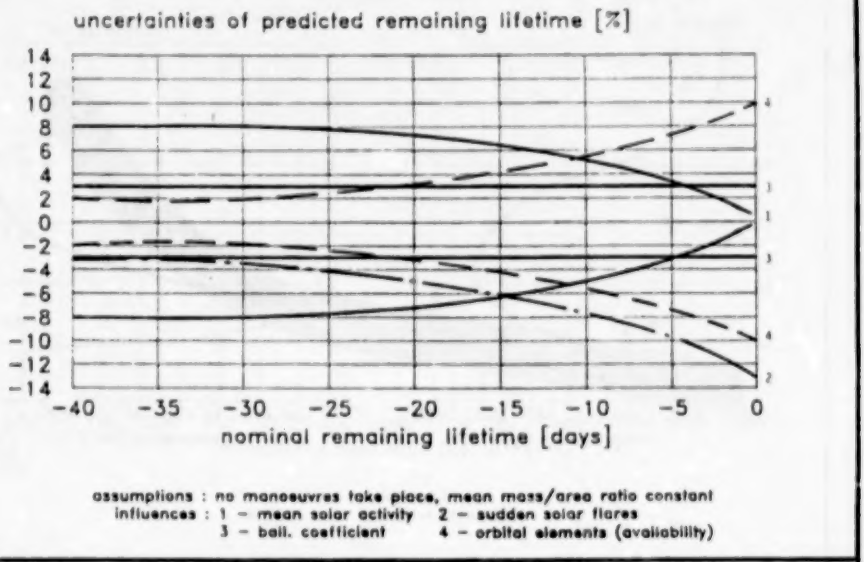


IRR TUBS

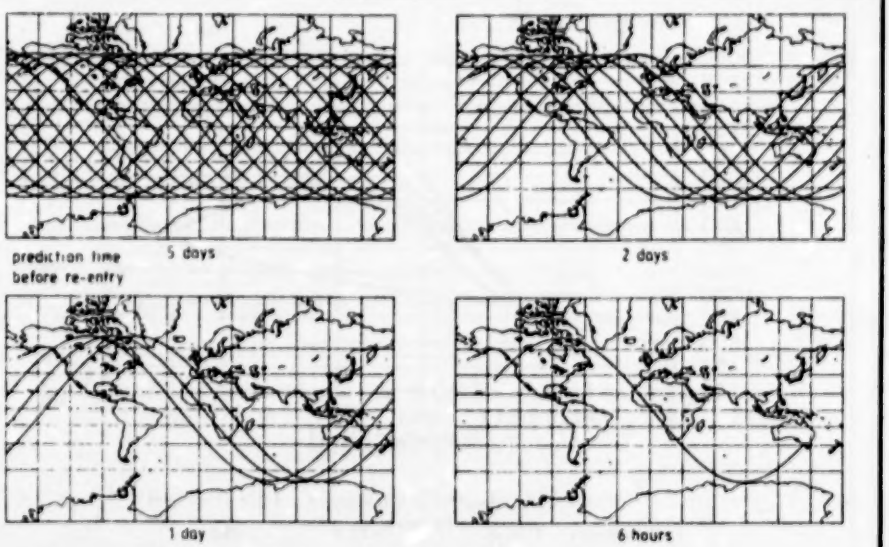
POSSIBLE NPS RE-ENTRY GROUND TRACKS ON WHICH AN IMPACT MAY OCCUR DUE TO ORBIT-INCLINATION

Fig.16

/...

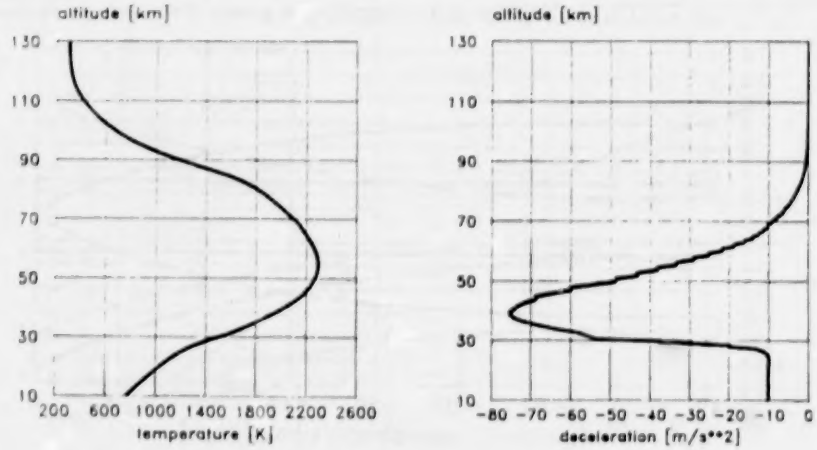


IFAR TUBS | UNCERTAINTIES OF RE-ENTRY PREDICTION AS FUNCTION OF THE TIME UNTIL RE-ENTRY | Fig.17

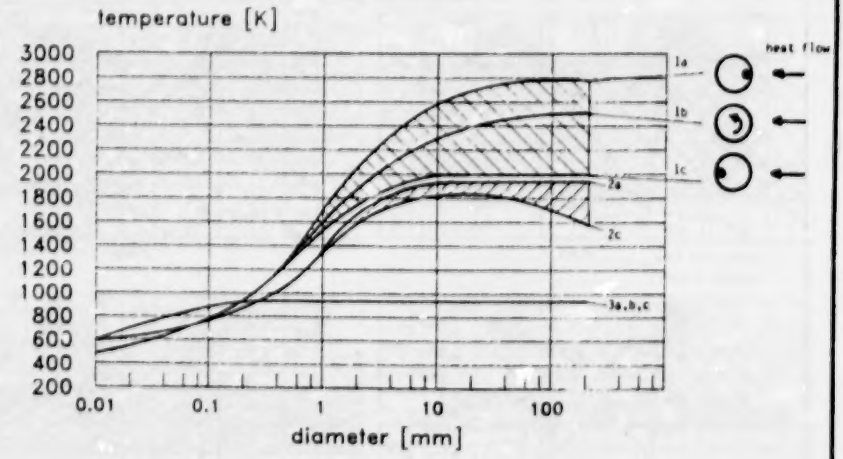


IFAR TUBS | NPS RE-ENTRY GROUND TRACKS, ON WHICH AN IMPACT MAY OCCUR ACCORDING TO PREDICTION UNCERTAINTY | Fig.18

/...

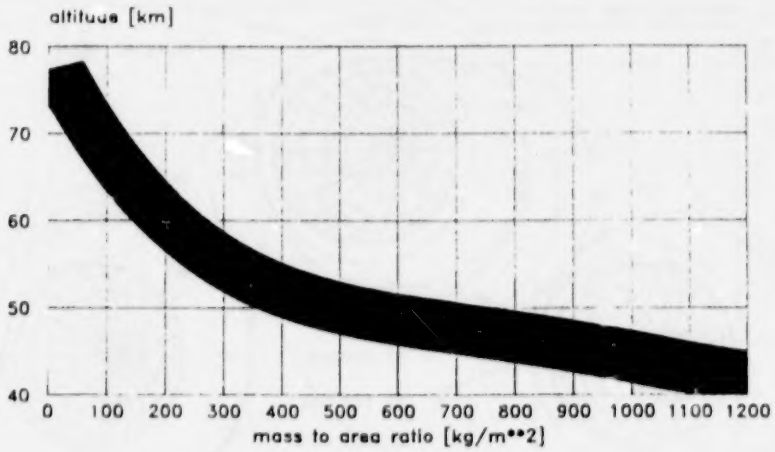


IRR TUBS	TEMPERATURE AND DECELERATION OF A BARE UO2 SPHERE UPON RE-ENTRY FROM A CIRCULAR ORBIT	Fig.19

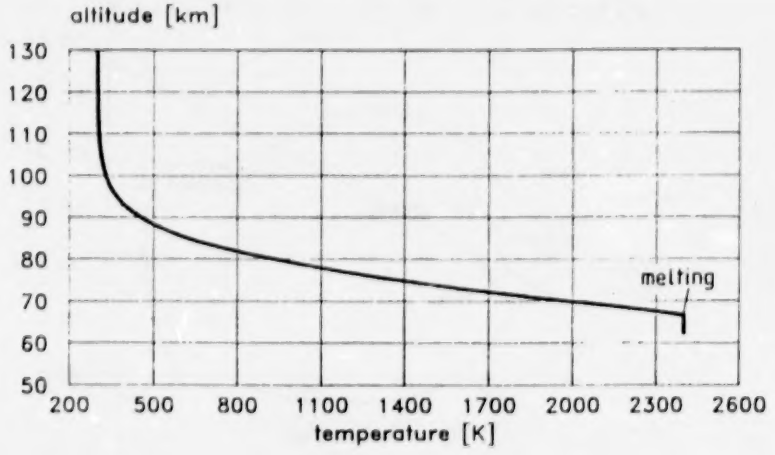


IRR TUBS	MAXIMUM TEMPERATURES OF SPHERES UPON RE-ENTRY FROM A CIRCULAR ORBIT	Fig.20

/...

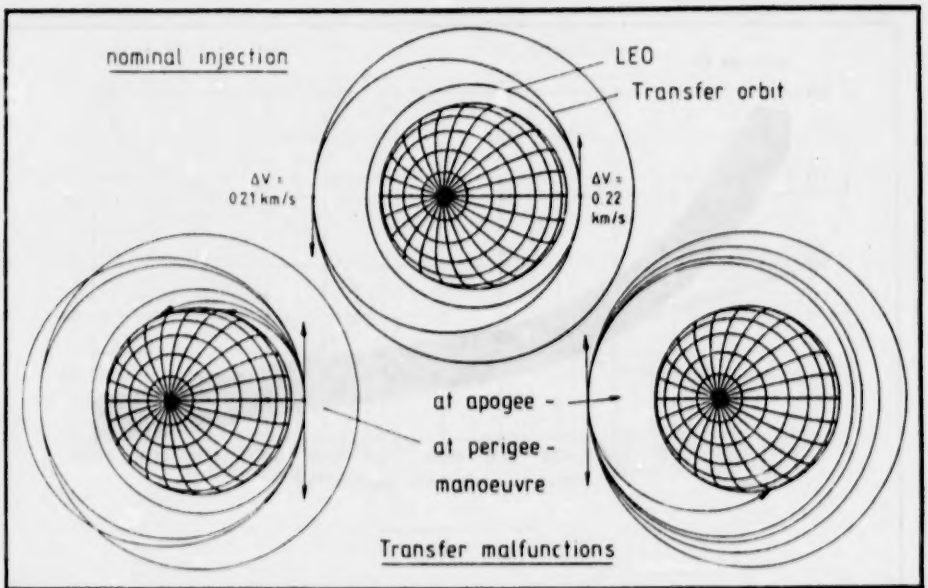


IRR TUBS	THE ALTITUDES OF MAXIMUM HEAT FLOW ON SPHERES UPON RE-ENTRY FROM A CIRCULAR ORBIT	Fig.21

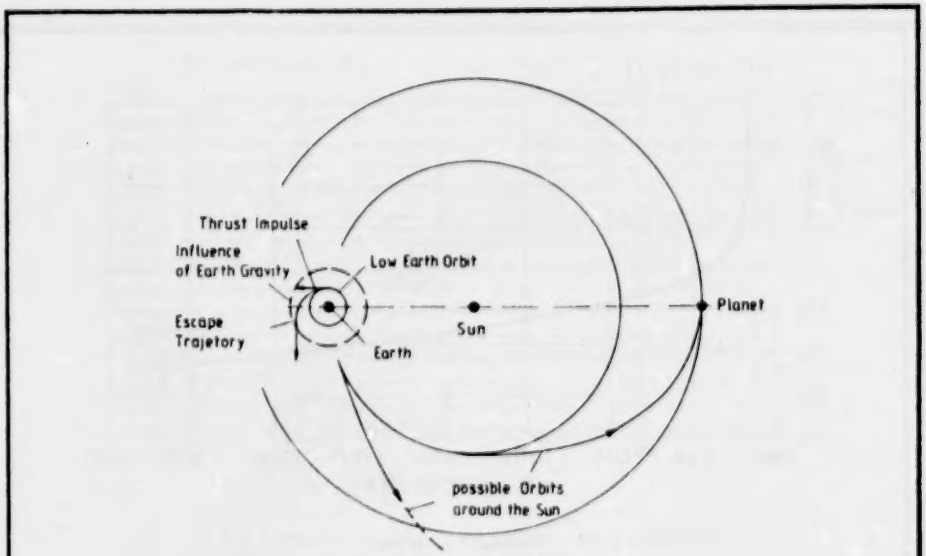


IRR TUBS	TEMPERATURE OF A BARE PUO2 SPHERE UPON RE-ENTRY FROM A HIGH ECCENTRIC ORBIT	Fig.22

/...

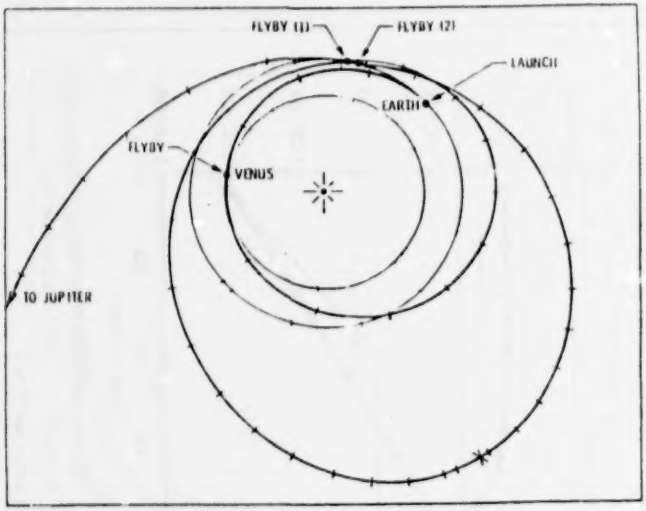


IFRR TUBS | POSSIBLE MALFUNCTIONS DURING ORBIT TRANSFER | Fig.23

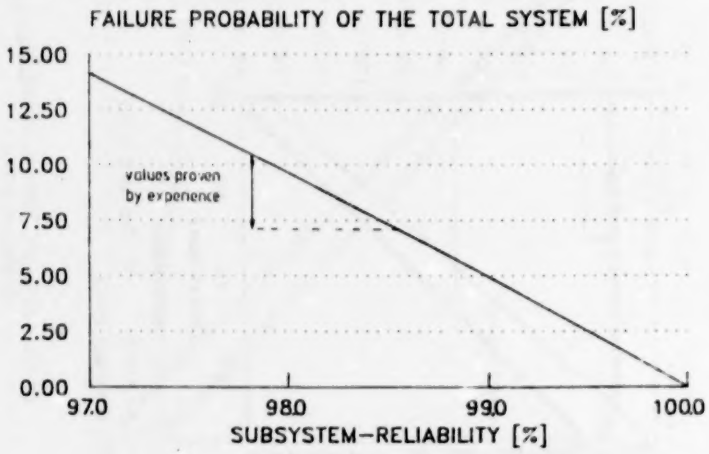


IFRR TUBS | DEEP SPACE MISSION (EXAMPLE) | Fig.24

/...

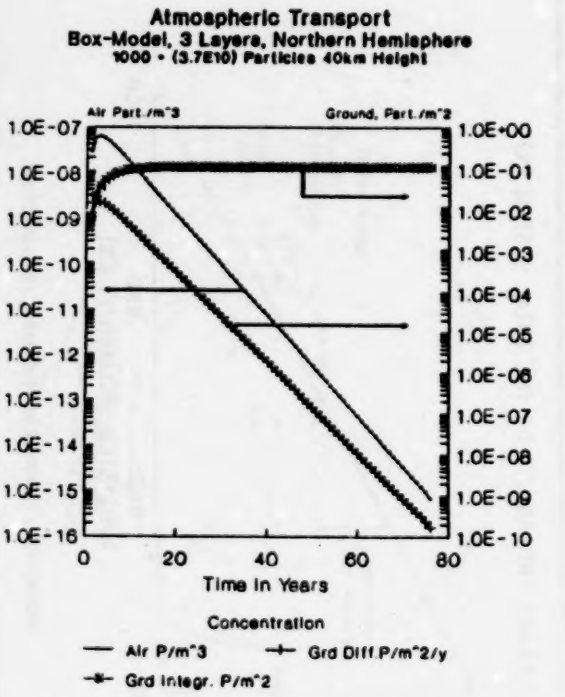


IRR TUBS	SWING-BY AT EARTH DURING A DEEP SPACE MISSION (EXAMPLE)	Fig.25



IRR TUBS	THE PROBALILITY OF A MALFUNCTION DURING AN ORBITAL TRANSFER AS FUNCTION OF SUBSYSTEM-RELIABILITY	Fig.26

/...


Atmospheric Transport
Box-Model, 3 Layers, Northern Hemisphere
1000 • (3.7E10) Particles 40km Height
Air Part./m^3
Ground, Part./m^2
1.0E-07
1.0E-08
1.0E-09
1.0E-10
1.0E-11
1.0E-12
1.0E-13
1.0E-14
1.0E-15
1.0E-16
1.0E+00
1.0E-01
1.0E-02
1.0E-03
1.0E-04
1.0E-05
1.0E-06
1.0E-07
1.0E-08
1.0E-09
1.0E-10
0
20
40
60
80
Time in Years
Concentration
Air P/m^3
Grd Diff.P/m^2/y
Grd Integr. P/m^2

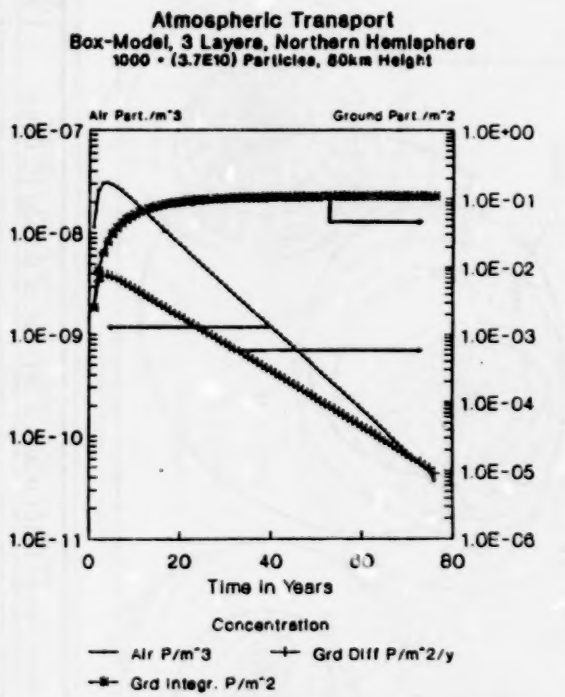

Atmospheric Transport
Box-Model, 3 Layers, Northern Hemisphere
1000 • (3.7E10) Particles, 80km Height
Air Part./m^3
Ground Part./m^2
1.0E-07
1.0E-08
1.0E-09
1.0E-10
1.0E-11
1.0E+00
1.0E-01
1.0E-02
1.0E-03
1.0E-04
1.0E-05
1.0E-06
0
20
40
60
80
Time in Years
Concentration
Air P/m^3
Grd Diff P/m^2/y
Grd Integr. P/m^2

Fig. 27

/...

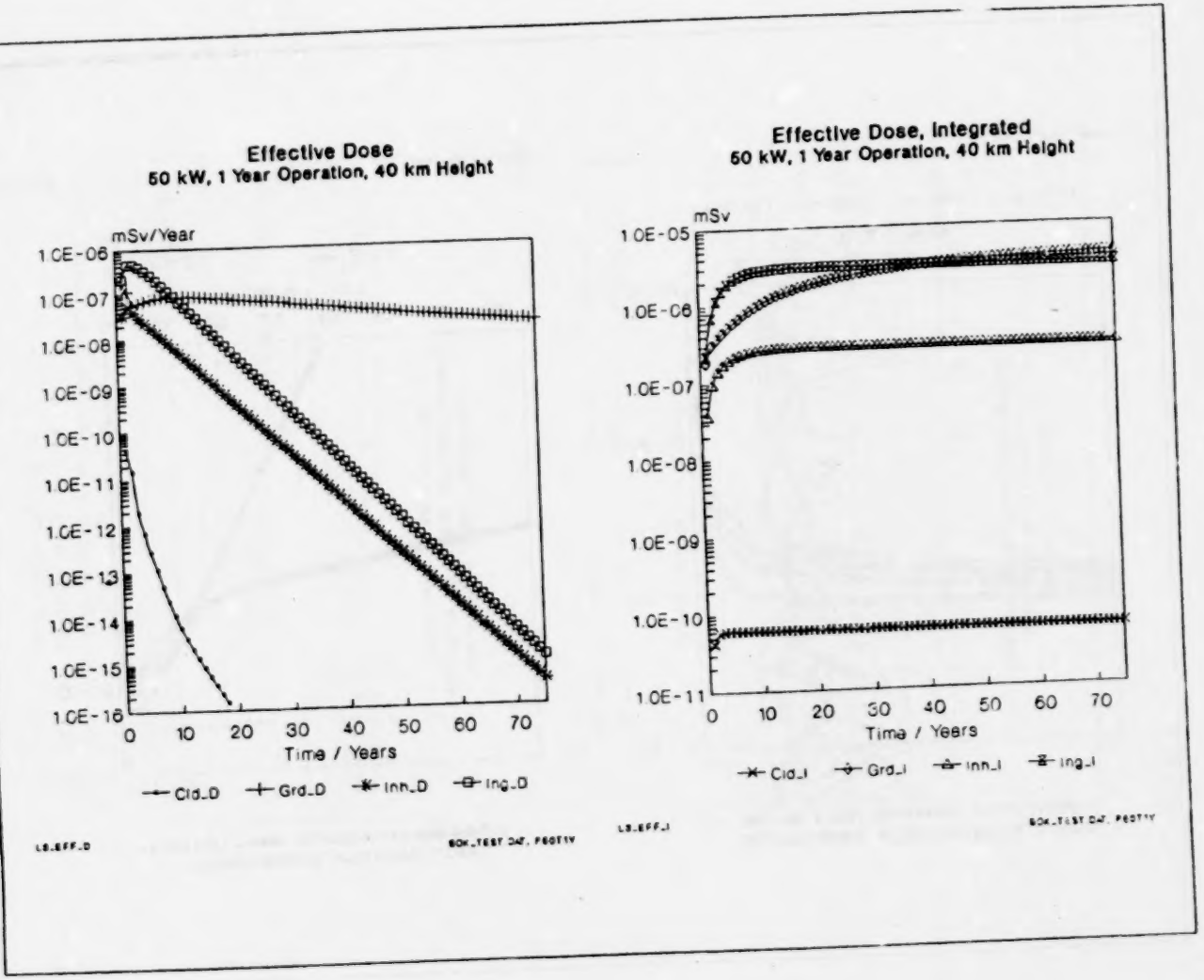

Effective Dose
50 kW, 1 Year Operation, 40 km Height
mSv/Year
1.0E-06
1.0E-07
1.0E-08
1.0E-09
1.0E-10
1.0E-11
1.0E-12
1.0E-13
1.0E-14
1.0E-15
1.0E-16
0
10
20
30
40
50
60
70
Time / Years
Cld_D
Grd_D
Inh_D
Ing_D
LB_EFF_D
Effective Dose, Integrated
50 kW, 1 Year Operation, 40 km Height
mSv
1.0E-05
1.0E-06
1.0E-07
1.0E-08
1.0E-09
1.0E-10
1.0E-11
0
10
20
30
40
50
60
70
Time / Years
Cld_I
Grd_I
Inh_I
Ing_I
LB_EFF_I

Fig. 28

/...

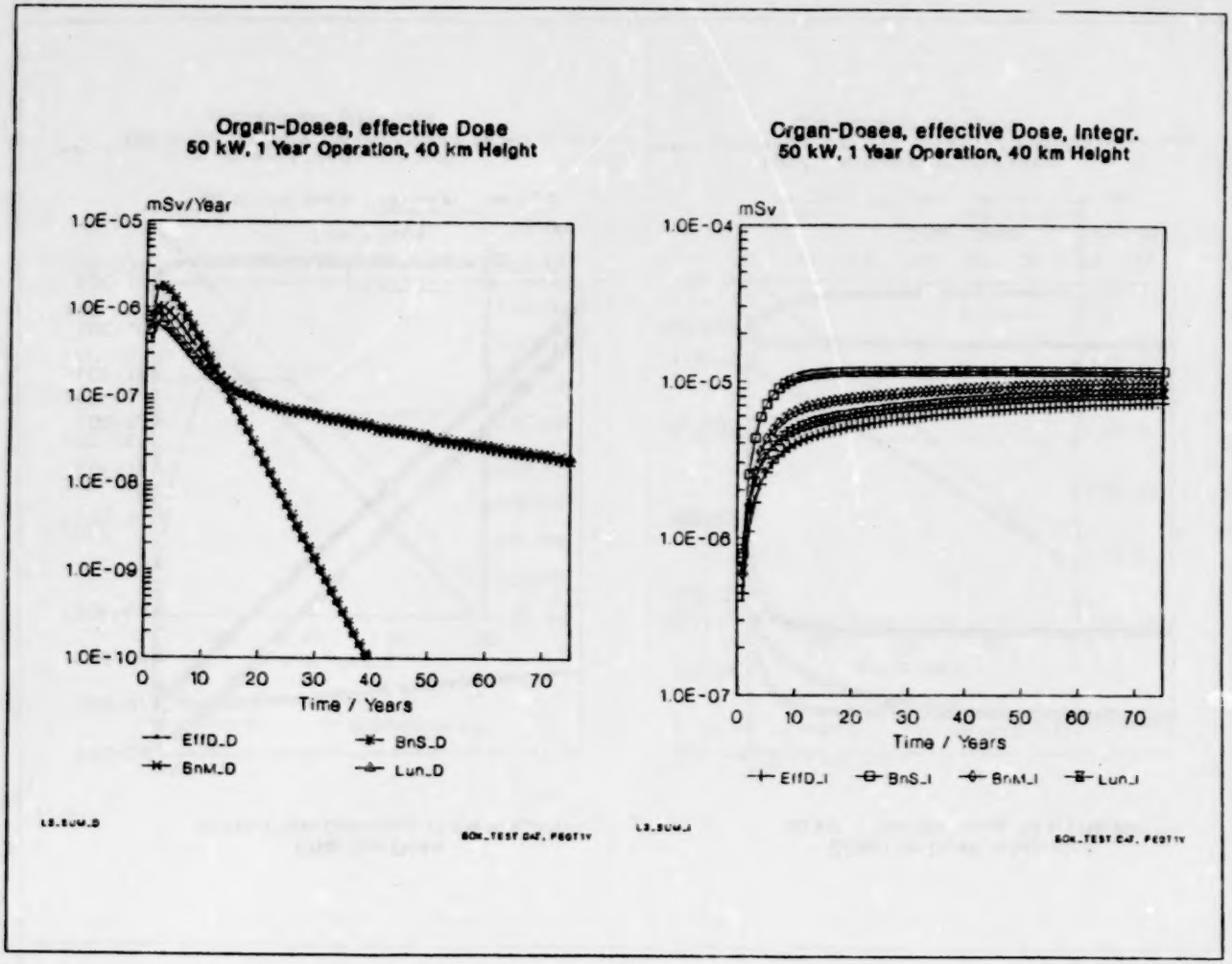

Organ-Doses, effective Dose
50 kW, 1 Year Operation, 40 km Height
mSv/Year
1.0E-05
1.0E-06
1.0E-07
1.0E-08
1.0E-09
1.0E-10
0
10
20
30
40
50
60
70
Time / Years
EffD_D
BnS_D
BnM_D
Lun_D
Organ-Doses, effective Dose, Integr.
50 kW, 1 Year Operation, 40 km Height
mSv
1.0E-04
1.0E-05
1.0E-06
1.0E-07
0
10
20
30
40
50
60
70
Time / Years
EffD_I
BnS_I
BnM_I
Lun_I

Fig. 29

/...

Fig. 30

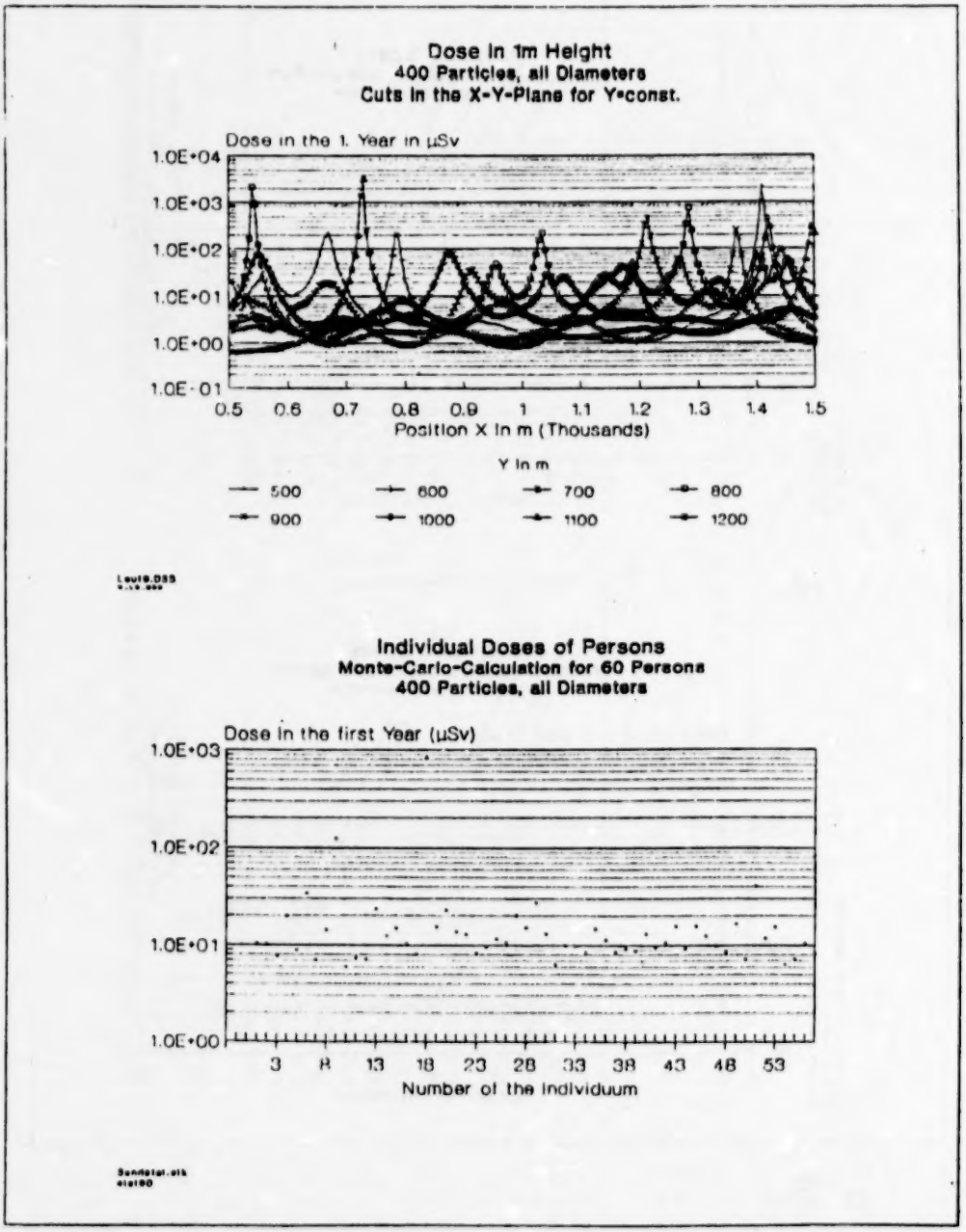
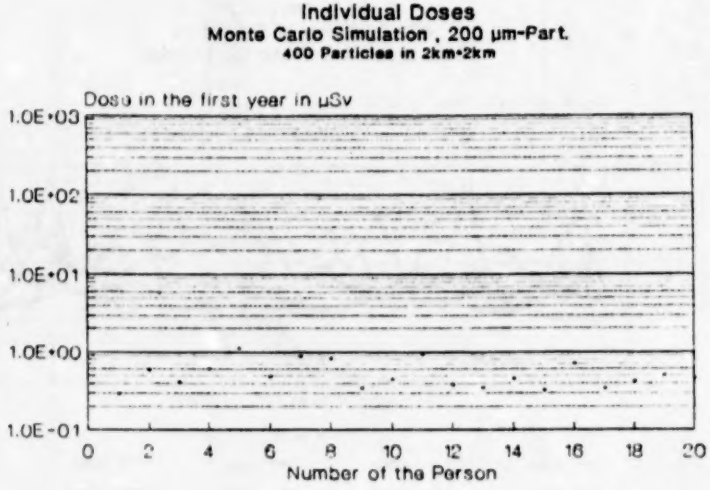

Dose in 1m Height
400 Particles, all Diameters
Cuts in the X-Y-Plane for Y=const.
Dose in the 1. Year in µSv
1.0E+04
1.0E+03
1.0E+02
1.0E+01
1.0E+00
1.0E-01
0.5 0.6 0.7 0.8 0.9 1 1.1 1.2 1.3 1.4 1.5
Position X in m (Thousands)
Y in m
500 600 700 800
900 1000 1100 1200
Individual Doses of Persons
Monte-Carlo-Calculation for 60 Persons
400 Particles, all Diameters
Dose in the first Year (µSv)
1.0E+03
1.0E+02
1.0E+01
1.0E+00
3 8 13 18 23 28 33 38 43 48 53
Number of the Individuum

Fig. 31

/...


Individual Doses
Monte Carlo Simulation , 200 µm-Part.
400 Particles in 2km*2km
Dose in the first year in µSv
1.0E+03
1.0E+02
1.0E+01
1.0E+00
1.0E-01
0
2
4
6
8
10
12
14
16
18
20
Number of the Person

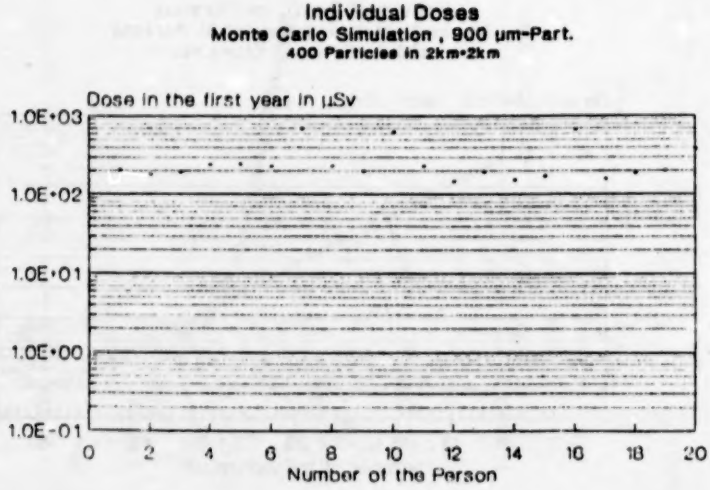

Individual Doses
Monte Carlo Simulation , 900 µm-Part.
400 Particles in 2km*2km
Dose in the first year in µSv
1.0E+03
1.0E+02
1.0E+01
1.0E+00
1.0E-01
0
2
4
6
8
10
12
14
16
18
20
Number of the Person

Fig. 32

/...

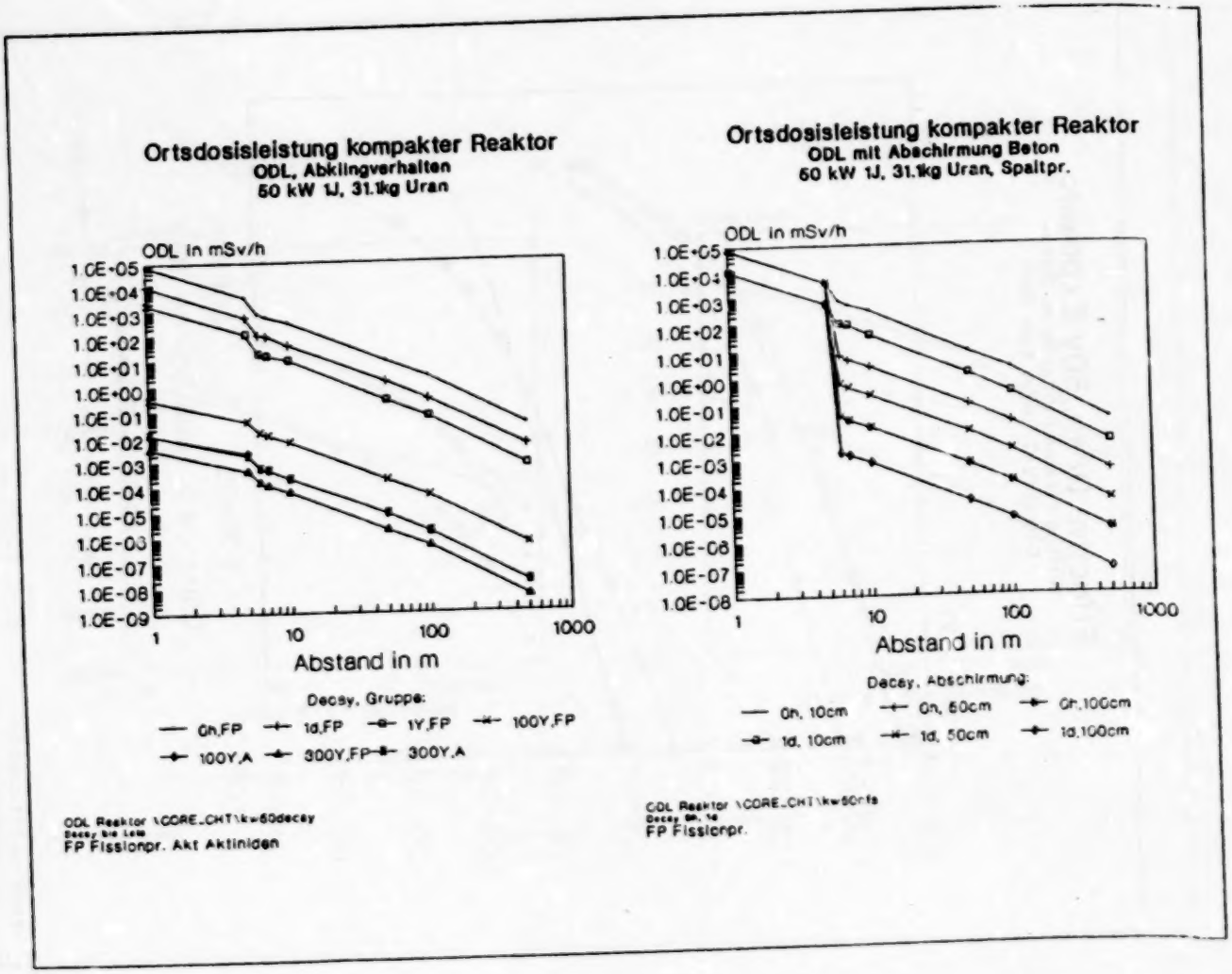

Ortsdosisleistung kompakter Reaktor
ODL, Abklingverhalten
50 kW 1J, 31.1kg Uran
ODL in mSv/h
1.0E+05
1.0E+04
1.0E+03
1.0E+02
1.0E+01
1.0E+00
1.0E-01
1.0E-02
1.0E-03
1.0E-04
1.0E-05
1.0E-06
1.0E-07
1.0E-08
1.0E-09
1
10
100
1000
Abstand in m
Decay, Gruppe:
0h,FP
1d,FP
1Y,FP
100Y,FP
100Y,A
300Y,FP
300Y,A
ODL Reaktor \CORE_CHT\kw50decay
Decay bis 1mA
FP Fissionpr. Akt Aktiniden
Ortsdosisleistung kompakter Reaktor
ODL mit Abschirmung Beton
50 kW 1J, 31.1kg Uran, Spaltpr.
ODL in mSv/h
1.0E+05
1.0E+04
1.0E+03
1.0E+02
1.0E+01
1.0E+00
1.0E-01
1.0E-02
1.0E-03
1.0E-04
1.0E-05
1.0E-06
1.0E-07
1.0E-08
1
10
100
1000
Abstand in m
Decay, Abschirmung:
0h, 10cm
0h, 50cm
0h,100cm
1d, 10cm
1d, 50cm
1d,100cm
ODL Reaktor \CORE_CHT\kw50rts
Decay 0h, 1d
FP Fissionpr.

Fig. 23

/...

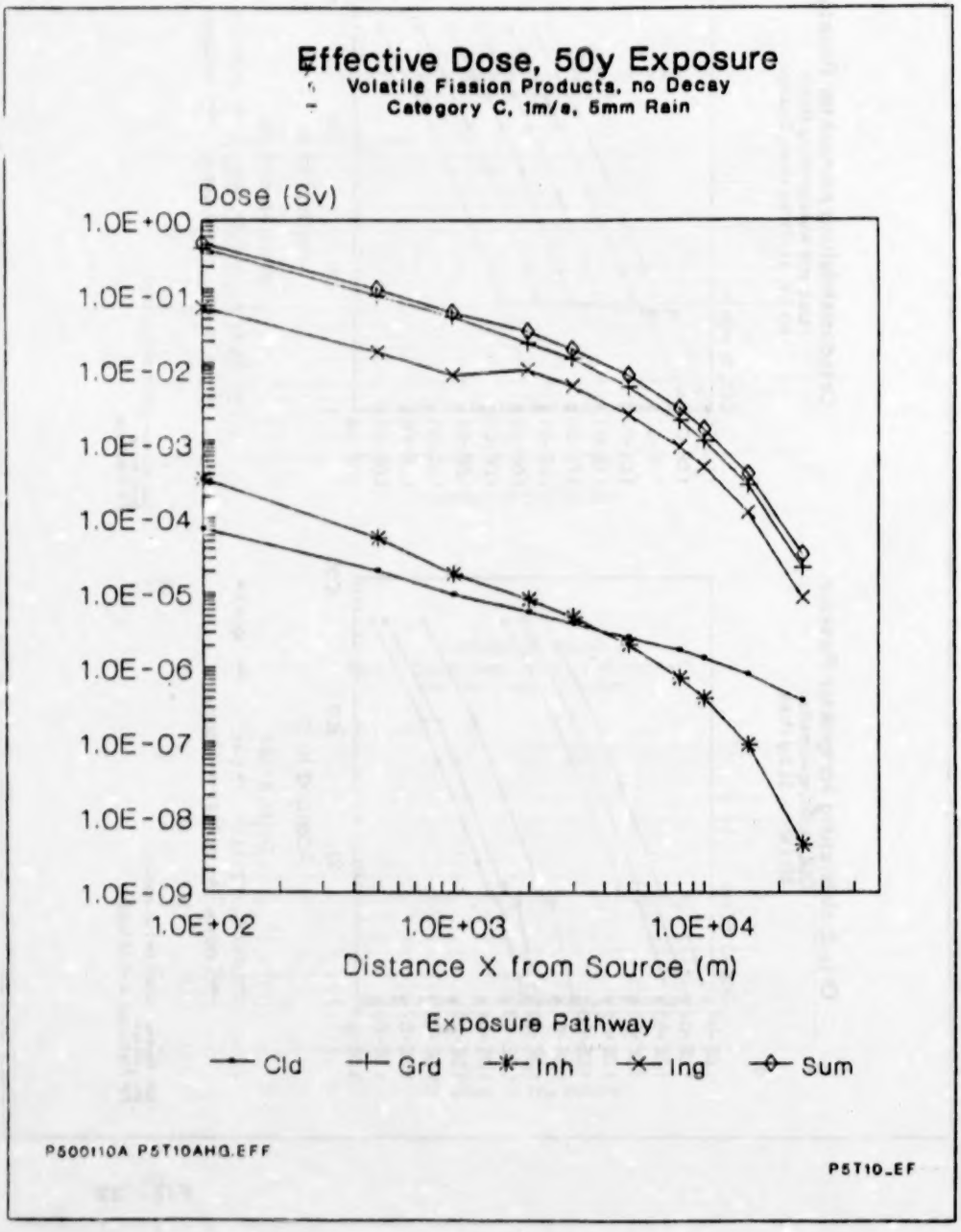

Effective Dose, 50y Exposure
Volatile Fission Products, no Decay
Category C, 1m/s, 5mm Rain
Dose (Sv)
1.0E+00
1.0E-01
1.0E-02
1.0E-03
1.0E-04
1.0E-05
1.0E-06
1.0E-07
1.0E-08
1.0E-09
1.0E+02
1.0E+03
1.0E+04
Distance X from Source (m)
Exposure Pathway
Cld
Grd
Inh
Ing
Sum
P500110A P5T10AHQ.EFF
P5T10_EF

Fig. 34

/...

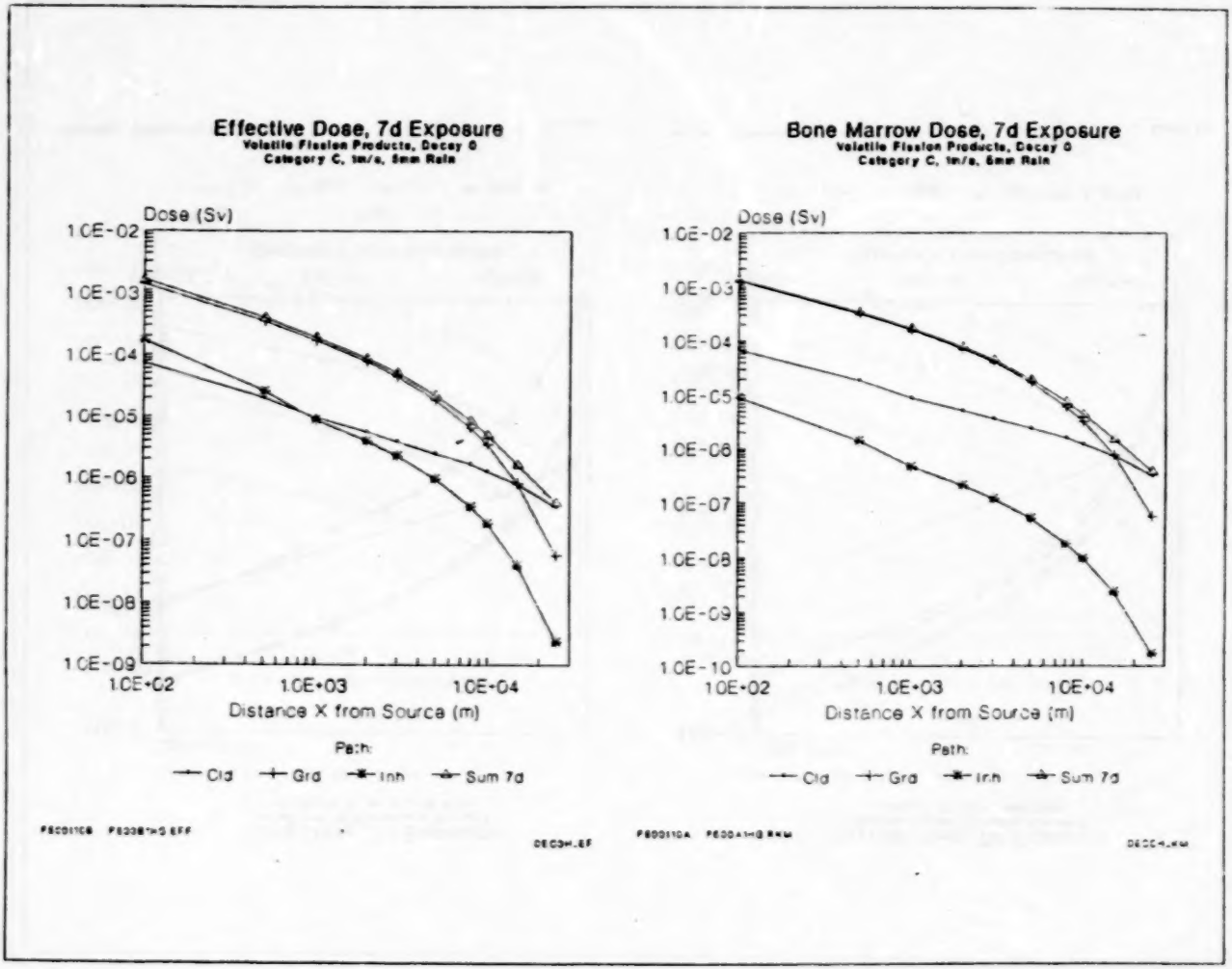

Effective Dose, 7d Exposure
Volatile Fission Products, Decay 0
Category C, 1m/s, 5mm Rain
Dose (Sv)
1.0E-02
1.0E-03
1.0E-04
1.0E-05
1.0E-06
1.0E-07
1.0E-08
1.0E-09
1.0E+02
1.0E+03
1.0E+04
Distance X from Source (m)
Path:
Cld
Grd
Inh
Sum 7d
Bone Marrow Dose, 7d Exposure
Volatile Fission Products, Decay 0
Category C, 1m/s, 5mm Rain
Dose (Sv)
1.0E-02
1.0E-03
1.0E-04
1.0E-05
1.0E-06
1.0E-07
1.0E-08
1.0E-09
1.0E-10
1.0E+02
1.0E+03
1.0E+04
Distance X from Source (m)
Path:
Cld
Grd
Inh
Sum 7d

Fig. 35

/...

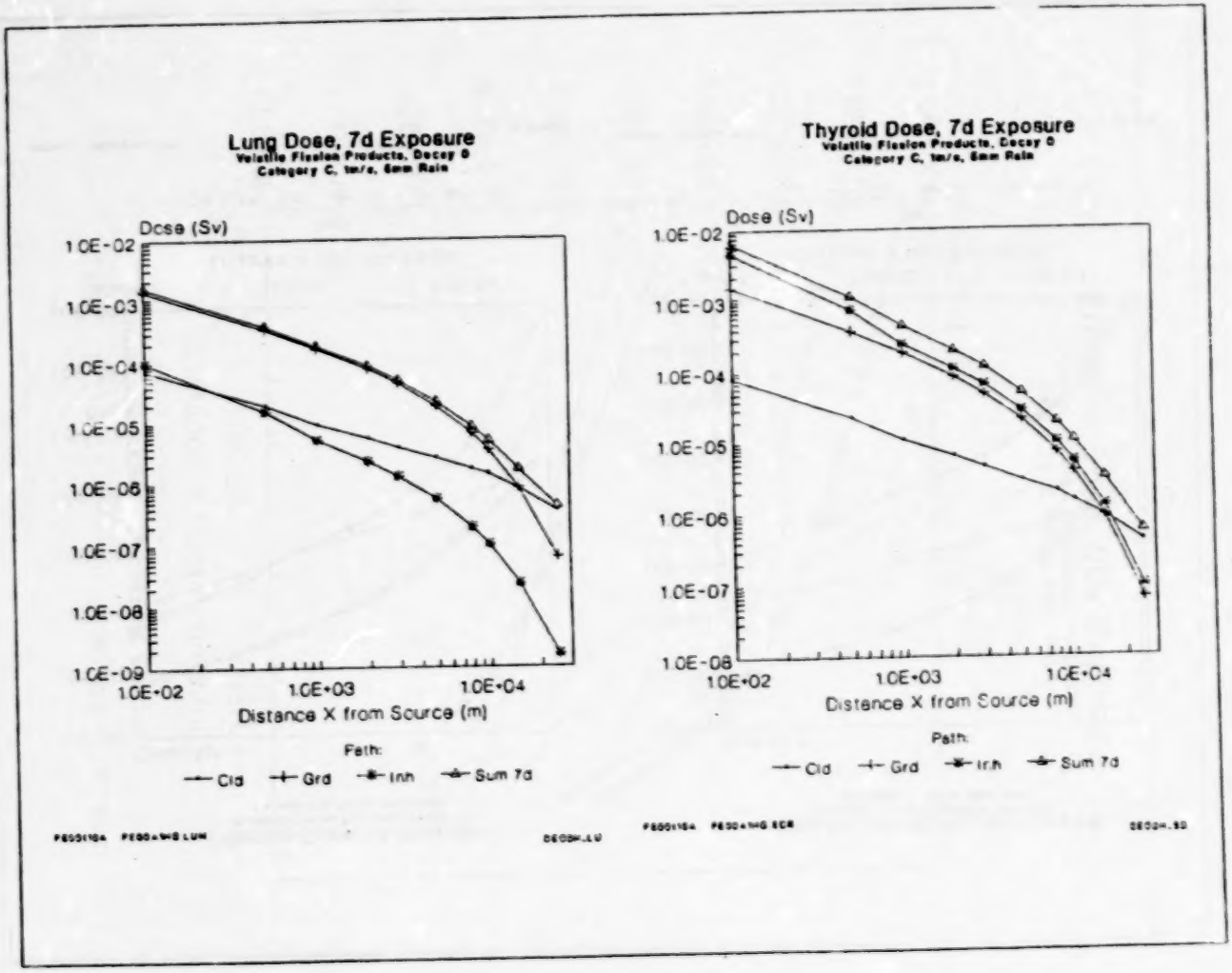

Lung Dose, 7d Exposure
Volatile Fission Products, Decay 0
Category C, 1m/s, 6mm Rain
Dose (Sv)
1.0E-02
1.0E-03
1.0E-04
1.0E-05
1.0E-06
1.0E-07
1.0E-08
1.0E-09
1.0E+02
1.0E+03
1.0E+04
Distance X from Source (m)
Path:
Cld
Grd
Inh
Sum 7d
Thyroid Dose, 7d Exposure
Volatile Fission Products, Decay 0
Category C, 1m/s, 6mm Rain
Dose (Sv)
1.0E-02
1.0E-03
1.0E-04
1.0E-05
1.0E-06
1.0E-07
1.0E-08
1.0E+02
1.0E+03
1.0E+04
Distance X from Source (m)
Path:
Cld
Grd
Inh
Sum 7d

Fig. 36

/...

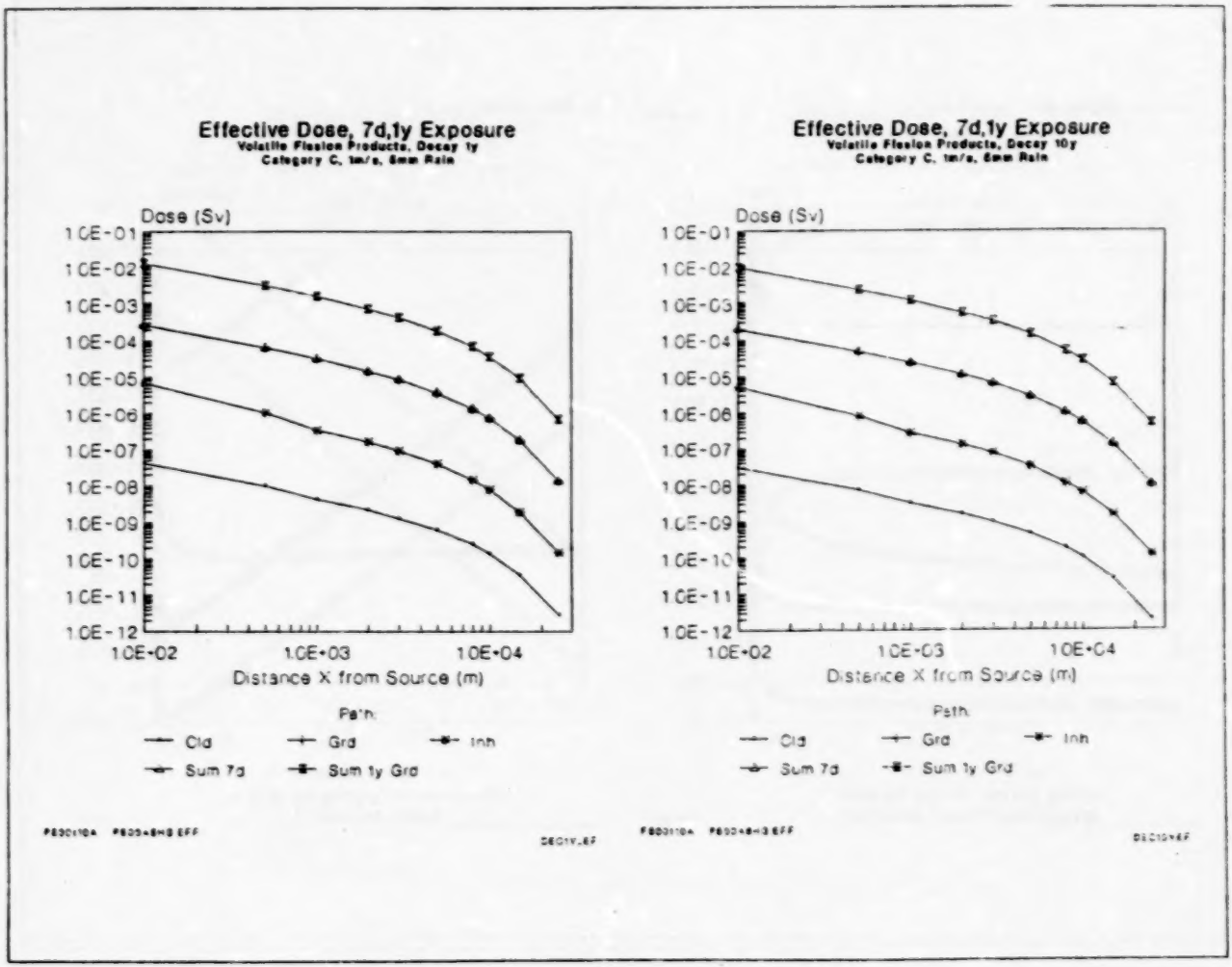

Effective Dose, 7d,1y Exposure
Volatile Fission Products, Decay 1y
Category C, 1m/s, 6mm Rain
Dose (Sv)
1.0E-01
1.0E-02
1.0E-03
1.0E-04
1.0E-05
1.0E-06
1.0E-07
1.0E-08
1.0E-09
1.0E-10
1.0E-11
1.0E-12
1.0E+02
1.0E+03
1.0E+04
Distance X from Source (m)
Path:
Cld
Grd
Inh
Sum 7d
Sum 1y Grd
Effective Dose, 7d,1y Exposure
Volatile Fission Products, Decay 10y
Category C, 1m/s, 6mm Rain
Dose (Sv)
1.0E-01
1.0E-02
1.0E-03
1.0E-04
1.0E-05
1.0E-06
1.0E-07
1.0E-08
1.0E-09
1.0E-10
1.0E-11
1.0E-12
1.0E+02
1.0E+03
1.0E+04
Distance X from Source (m)
Path:
Cld
Grd
Inh
Sum 7d
Sum 1y Grd

Fig. 37

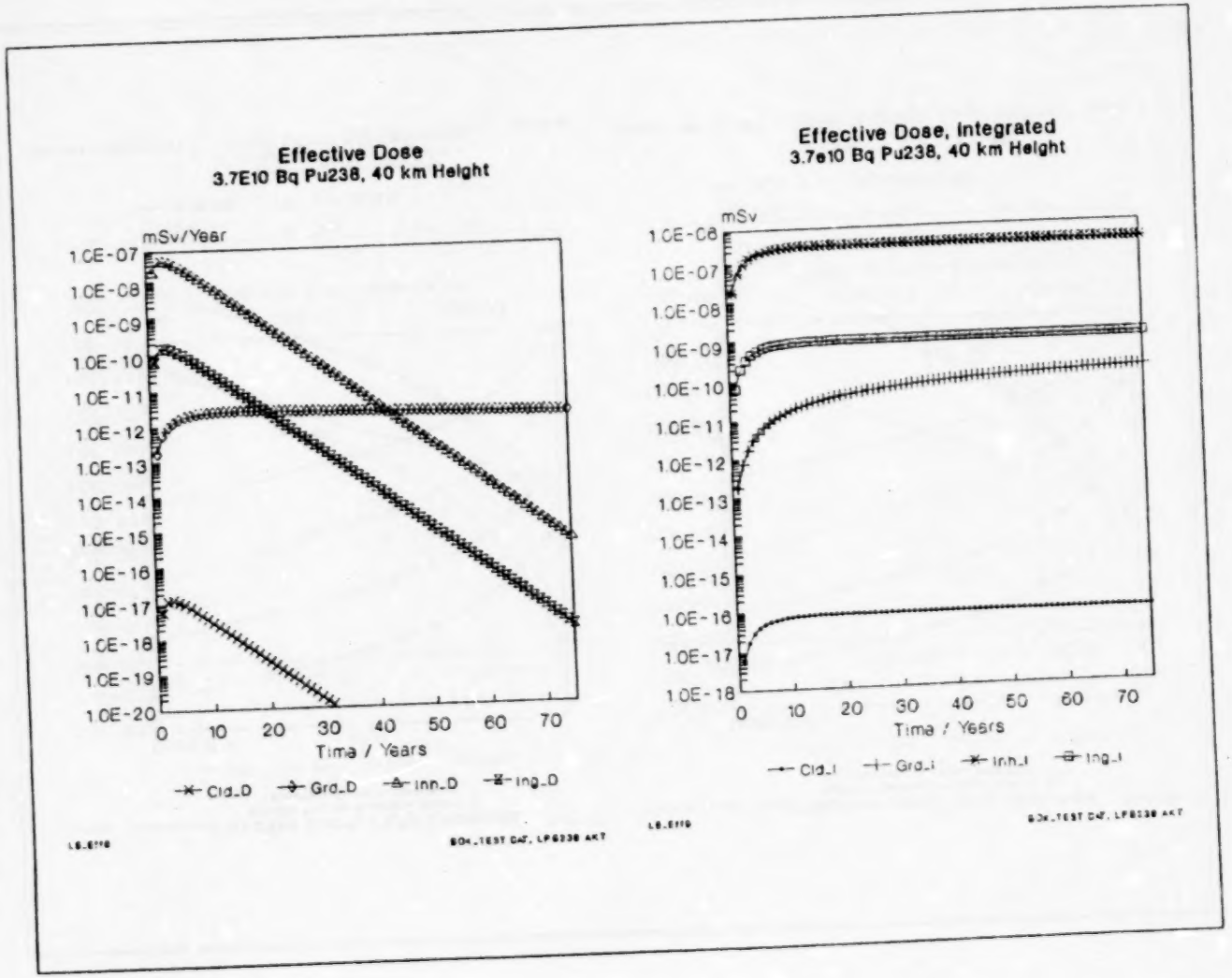

Effective Dose
3.7E10 Bq Pu238, 40 km Height
mSv/Year
1.0E-07
1.0E-08
1.0E-09
1.0E-10
1.0E-11
1.0E-12
1.0E-13
1.0E-14
1.0E-15
1.0E-16
1.0E-17
1.0E-18
1.0E-19
1.0E-20
0
10
20
30
40
50
60
70
Time / Years
Cld_D
Grd_D
Inh_D
Ing_D
Effective Dose, Integrated
3.7e10 Bq Pu238, 40 km Height
mSv
1.0E-06
1.0E-07
1.0E-08
1.0E-09
1.0E-10
1.0E-11
1.0E-12
1.0E-13
1.0E-14
1.0E-15
1.0E-16
1.0E-17
1.0E-18
0
10
20
30
40
50
60
70
Time / Years
Cld_I
Grd_I
Inh_I
Ing_I

Fig. 38

/...

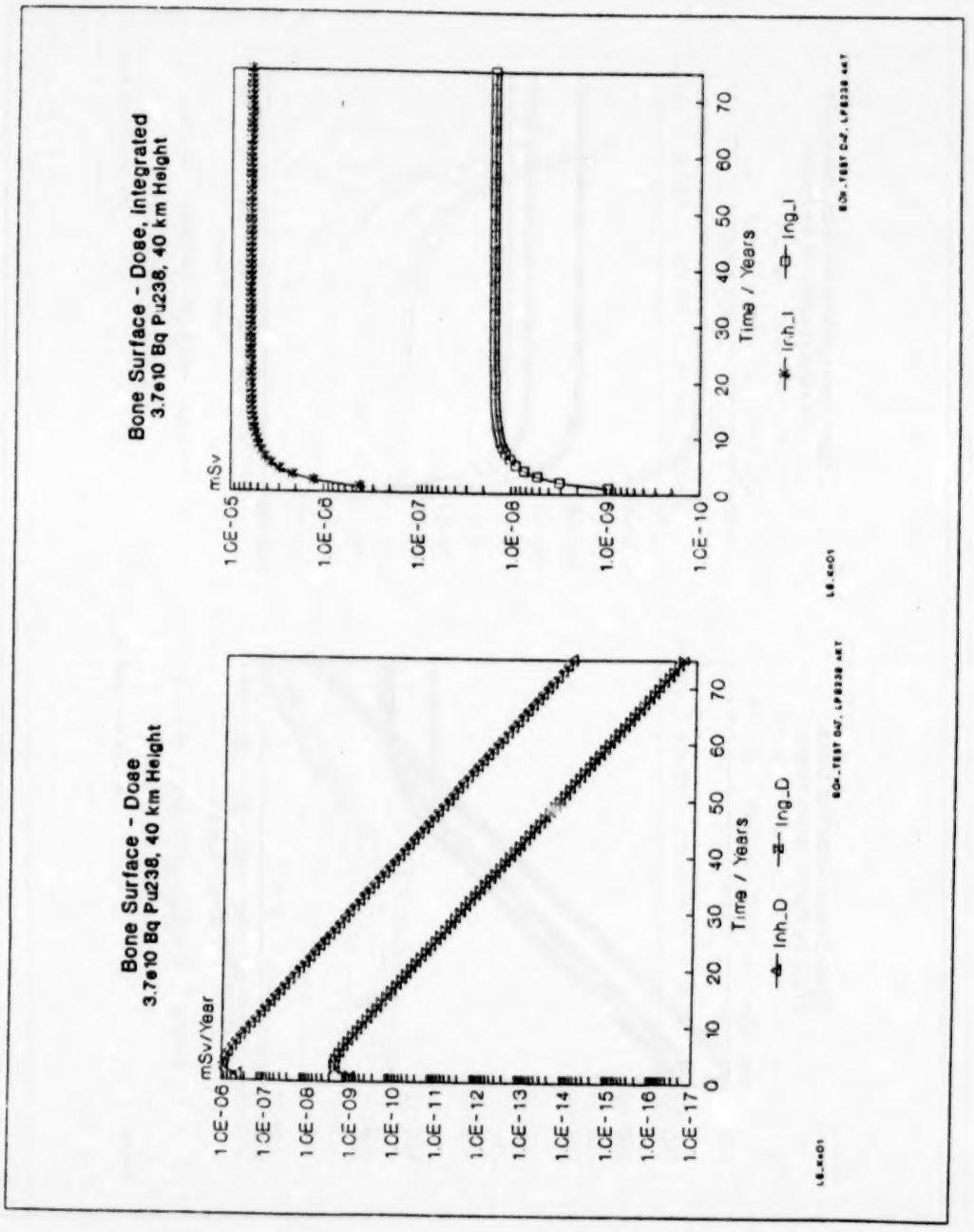

Bone Surface - Dose
3.7e10 Bq Pu238, 40 km Height
mSv/Year
1.0E-06
1.0E-07
1.0E-08
1.0E-09
1.0E-10
1.0E-11
1.0E-12
1.0E-13
1.0E-14
1.0E-15
1.0E-16
1.0E-17
0 10 20 30 40 50 60 70
Time / Years
Inh_D
Ing_D
Bone Surface - Dose, Integrated
3.7e10 Bq Pu238, 40 km Height
mSv
1.0E-05
1.0E-06
1.0E-07
1.0E-08
1.0E-09
1.0E-10
0 10 20 30 40 50 60 70
Time / Years
Inh_I
Ing_I

Fig. 39

/...

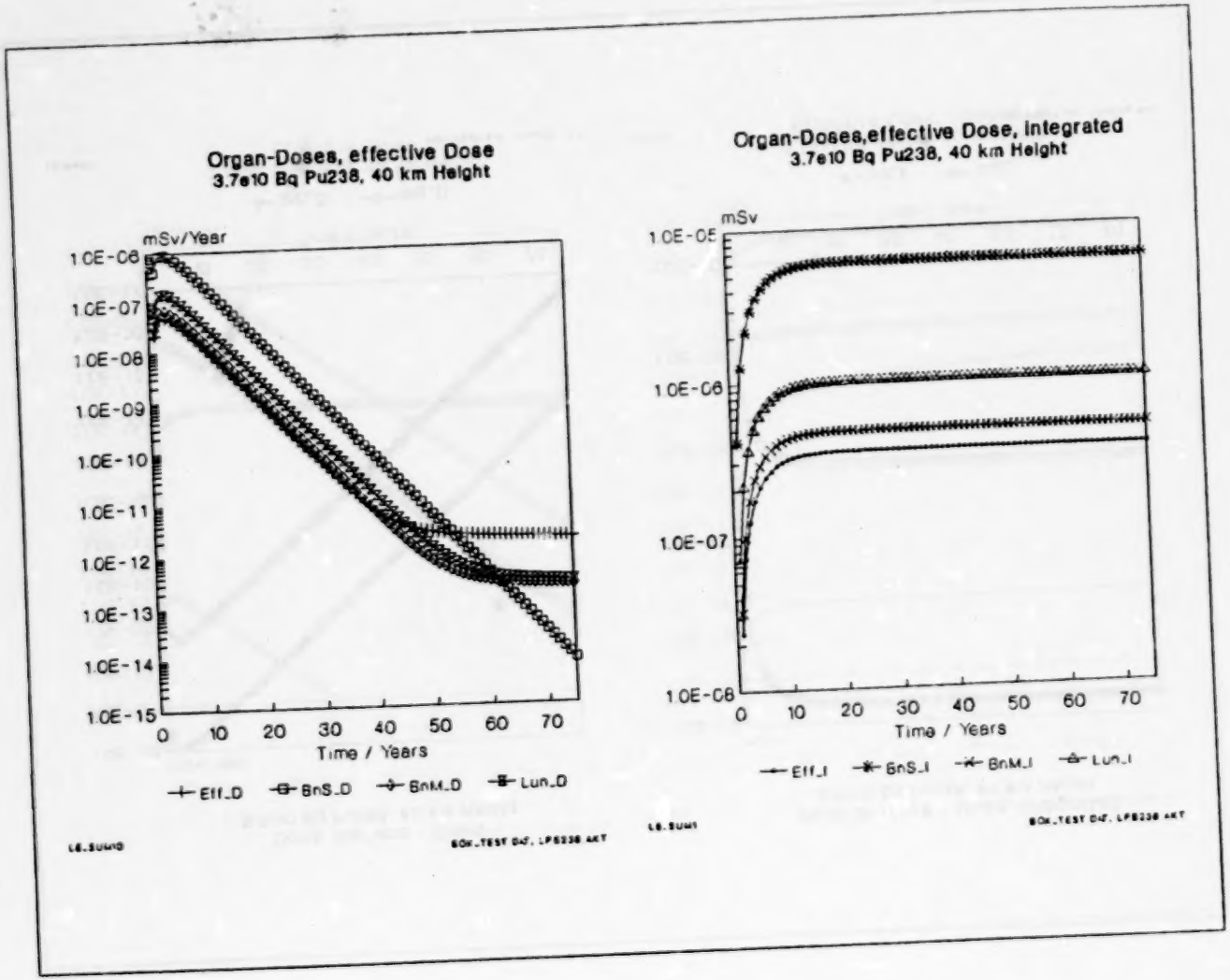

Organ-Doses, effective Dose
3.7e10 Bq Pu238, 40 km Height
mSv/Year
1.0E-06
1.0E-07
1.0E-08
1.0E-09
1.0E-10
1.0E-11
1.0E-12
1.0E-13
1.0E-14
1.0E-15
0 10 20 30 40 50 60 70
Time / Years
Eff_D BnS_D BnM_D Lun_D
Organ-Doses,effective Dose, Integrated
3.7e10 Bq Pu238, 40 km Height
mSv
1.0E-06
1.0E-07
1.0E-08
0 10 20 30 40 50 60 70
Time / Years
Eff_I BnS_I BnM_I Lun_I

Fig. 40

/...

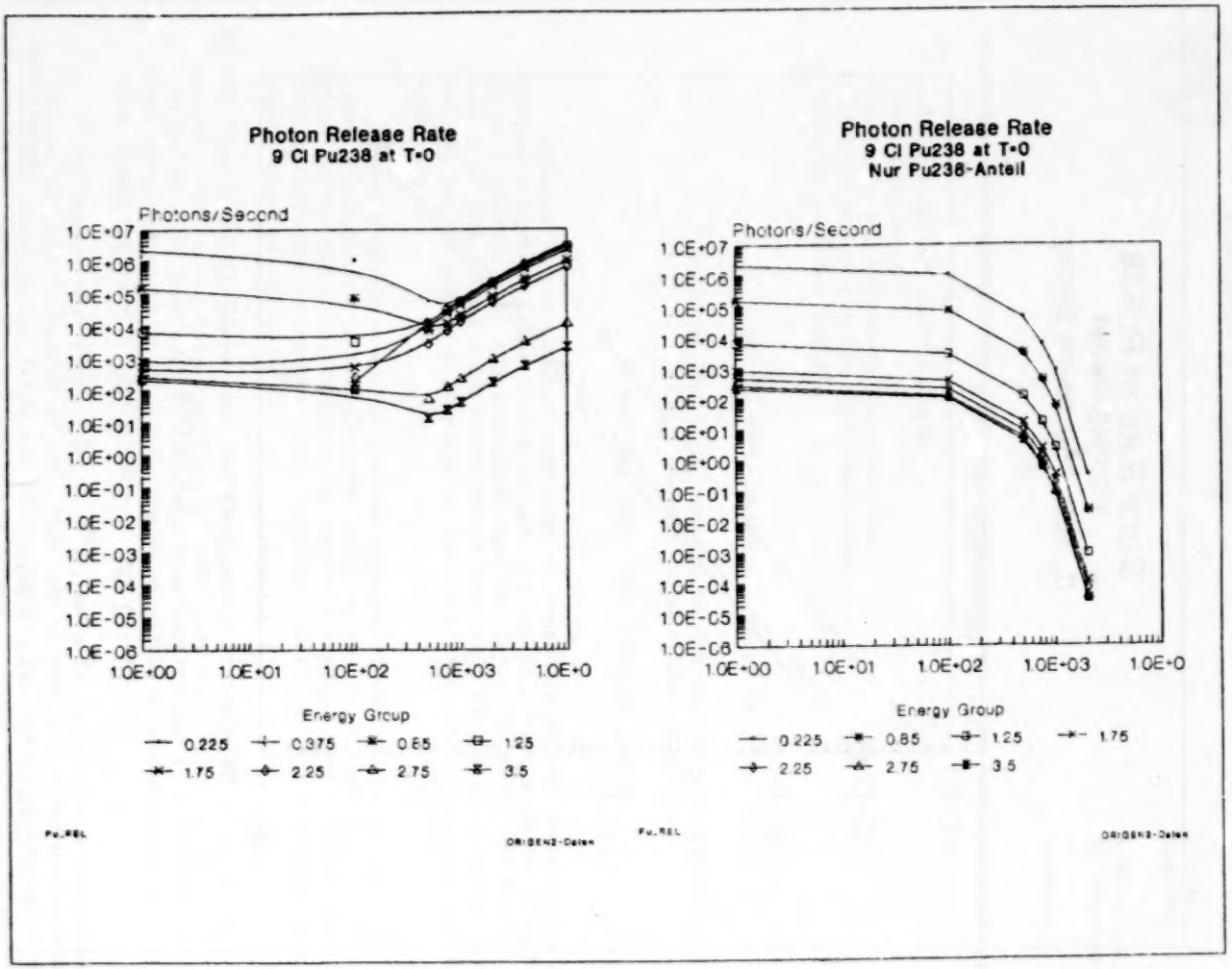

Photon Release Rate
9 Cl Pu238 at T•0
Photons/Second
1.0E+07
1.0E+06
1.0E+05
1.0E+04
1.0E+03
1.0E+02
1.0E+01
1.0E+00
1.0E-01
1.0E-02
1.0E-03
1.0E-04
1.0E-05
1.0E-06
1.0E+00
1.0E+01
1.0E+02
1.0E+03
1.0E+0
Energy Group
0.225
0.375
0.85
1.25
1.75
2.25
2.75
3.5
Photon Release Rate
9 Cl Pu238 at T•0
Nur Pu238-Anteil
Photons/Second
1.0E+07
1.0E+06
1.0E+05
1.0E+04
1.0E+03
1.0E+02
1.0E+01
1.0E+00
1.0E-01
1.0E-02
1.0E-03
1.0E-04
1.0E-05
1.0E-06
1.0E+00
1.0E+01
1.0E+02
1.0E+03
1.0E+0
Energy Group
0.225
0.85
1.25
1.75
2.25
2.75
3.5

Fig. 41

/...

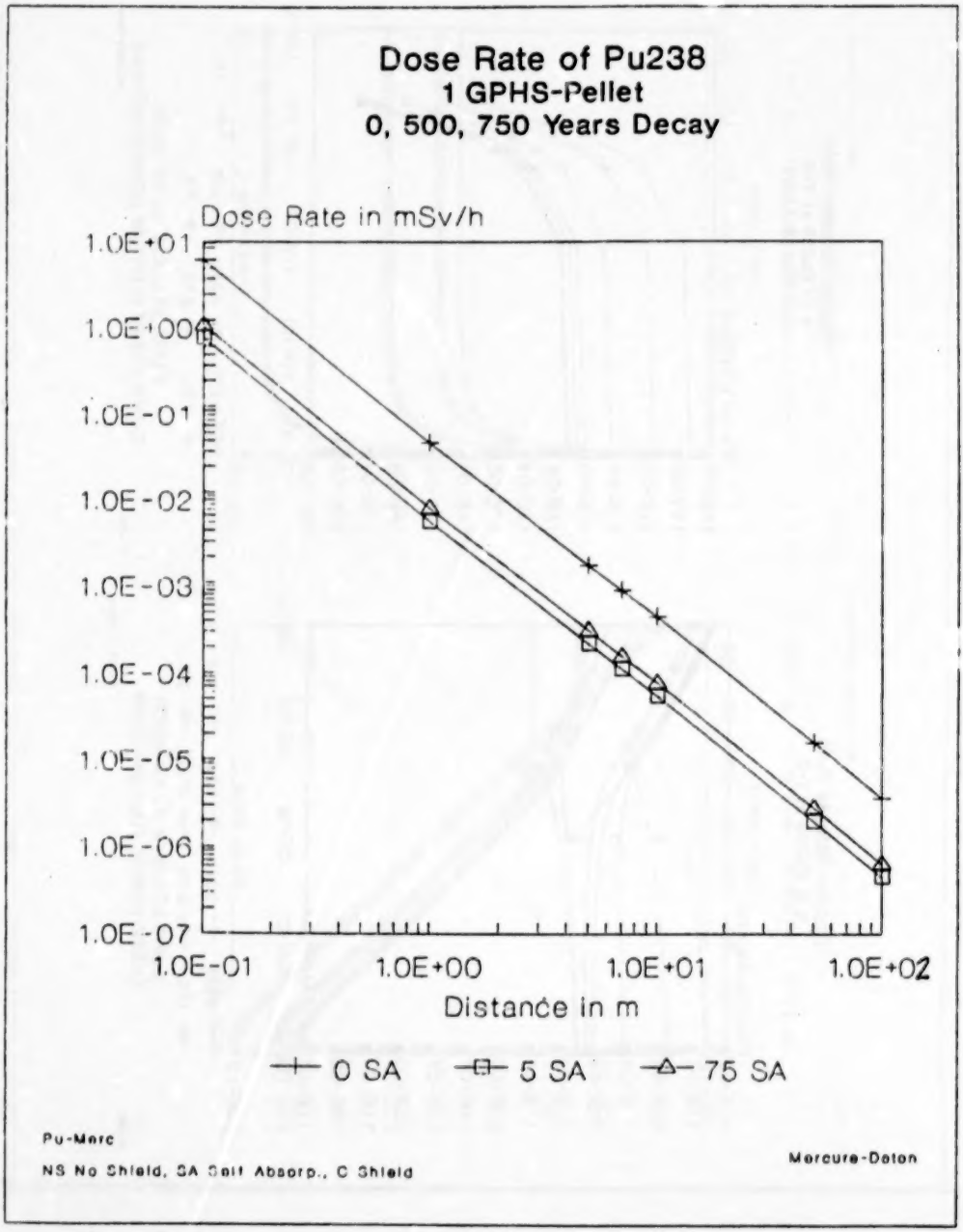

Dose Rate of Pu238
1 GPHS-Pellet
0, 500, 750 Years Decay
Dose Rate in mSv/h
1.0E+01
1.0E+00
1.0E-01
1.0E-02
1.0E-03
1.0E-04
1.0E-05
1.0E-06
1.0E-07
1.0E-01
1.0E+00
1.0E+01
1.0E+02
Distance in m
0 SA
5 SA
75 SA
Pu-Merc
NS No Shield, SA Self Absorp., C Shield
Mercure-Daton

Fig. 42

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General Assembly

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A/AC.105/C.1/WG.5/L.26
22 February 1990

ORIGINAL: ENGLISH

COMMITTEE ON THE PEACEFUL USES
OF OUTER SPACE
Scientific and Technical Sub-Committee
Working Group on the Use of Nuclear Power
Sources in Outer Space

USE OF NUCLEAR POWER SOURCES IN OUTER SPACE

Problem of the early warning of the re-entry of a satellite with a nuclear power source on board

Working paper submitted by Canada

A major unknown in our knowledge of satellite orbits, whether the satellite carries a nuclear power source or not, is the uncertainty of the time of re-entry of such objects into the atmosphere and the impact point on the Earth's surface. Such time and location information are important if the re-entering material puts the health and safety of the nearby population at risk over an extended period of time.

These uncertainties are the consequence of variations in the density of the Earth's atmosphere in the altitude range of about 150-300 km. The density has been observed to change both seasonally and on a shorter term. The density is also highly dependent on random solar activity, which heats and expands the atmosphere into higher altitudes.

Studies have shown that the uncertainty of the time of re-entry is about 10 per cent of the estimated time of remaining in orbit. As the last orbit has a period of just less than 90 minutes, this uncertainty is almost 9 minutes. This is equivalent to about 4,000 km along the satellite's ground track or 2 1/2 hours of time zones.

One method that might seem to offer help is to provide a satellite with a beacon, a radio "flashing light", that can be easily tracked by a simple radio receiver tuned to the frequency of the beacon for use while the satellite is still orbiting. Indeed, the various signals sent from the satellite to ground used for the transmission of experimental and housekeeping data have been used for this

purpose by active amateurs. However, these transmissions may cease owing to an internal failure, or the launching State, for its own reasons, may not wish its satellite to be easily identified and tracked. Such beacons, if continuously used, would also crowd the already restricted radio frequency bands.

In any event, such beacons have one major weakness: they probably will not survive re-entry or impact with the Earth's surface. This is the time when such beacons are most needed.

The problem of locating downed aircraft, distressed ships at sea or even an individual lost in the Arctic has been solved using a system that may have application to the satellite problem. This is the COSPAS-SARSAT system and is a joint satellite-based system of the United States of America, Canada, France and the Union of Soviet Socialist Republics designed to assist in search-and-rescue operations. It uses beacons which are operated only under distress conditions on agreed and designated frequencies. COSPAS is the USSR equivalent of "space system for search of vessels in distress". SARSAT stands for "search-and-rescue satellite aided tracking".

The system used for downed aircraft provides the closest parallel for possible use for satellites. A beacon, a small radio transmitter and batteries are placed in an airfoil, which is of a wing shape. This airfoil is attached to the outside of the tail of an aircraft. The shock of impact releases it before it is consumed in the wreckage. The beacon's motion and shape cause it to fly away from the immediate vicinity of the crash. Its flying action also slows it down sufficiently so that it can survive its own impact. The beacon carried aboard aircraft can be activated automatically by the shock of a violent manoeuvre or upon impact. The version of interest transmits on 406 MHz and weighs about 2 kg. Digital encoding is also available to indicate the country of origin and identification of the aircraft in distress.

The signal is received by polar orbiting satellites that can store the signal, the time it was received and sufficient Doppler (frequency change) information to provide location. These satellites, of which there are four currently in orbit, then dump this information at the next local user's terminal (LUT) within its line of sight. If there is an LUT in sight, retransmission may be instantaneous. The mission control centre confirms the reception of the signal and activates the search-and-rescue unit. Some exercise data suggest that the waiting times from impact to confirmation at a mission control centre will be less than 90 minutes, with a probability of 92 per cent. This delay is primarily due to the waiting time for a satellite to be in a position to receive the distress data from the ground and then to be in the line of sight of a local user's terminal. Receiving stations covered most of the Northern Hemisphere in 1986.

The 406-MHz signal can also be received by some geostationary satellites as long as the impact point is between 70° north and south latitudes. In this case there will essentially be an instantaneous retransmission of the signal, thereby providing the exact time that the beacon was activated. However, there will be no precise location information.

The purpose of the present paper is to suggest the possibility of using the COSPAS-SARSAT system to solve the problem of the early warning of re-entry of satellites. The main problem will be to redesign the 406-MHz beacon for space-based use. However, from an initial consideration, there do not appear to be any a priori limitations that would prohibit a successful design. The beacon is the only component that would require redesign to give the SARSAT system a downed-satellite capability.

During the normal use of the satellite, the transmitter will not be operating, but must be capable of working with little delay in times of emergencies. For reliability under unexpected conditions, the transmitter's power supply should be independent of the space vehicle's power supply (except possibly for a small battery charger), have a lifetime comparable to the satellite's lifetime in low Earth orbit and be capable of tolerating the low temperatures in orbit. The beacon must be able to survive the heat generated at the time of re-entry.

The beacon must also be able to survive the impact of the satellite. This can be achieved by the separation of the beacon from the satellite before impact, using the knowledge gained from the experience with the aircraft version. Such separation can be initiated by the heat of re-entry or by a device such as a pressure-sensitive switch. Reliability analysis could be applied to assist in choosing the best approach. For adequate separation, an airfoil would be used which was designed to have a ballistic coefficient β in the range 10-100. High β means a high mass-to-drag ratio, i.e., more streamlined (like an arrow); low β shapes can be considered like a falling leaf. Low β will permit more dispersion across the track due to any local winds; higher β shapes are less sensitive to this effect. Low β results in lower impact velocities than high β. The Cosmos 954 experience suggests that the airfoil could be designed not to be blown more than 10 km to one side of the projected ground track of the satellite. This deflection can be predicted to some extent from local wind data. Such a shape could also have an impact velocity low enough so that survival would be highly probable. A major problem will be to enable the beacon's transmitter and power supply to tolerate the intense level of ionizing radiation generated by the reactor. As the shadow shield will be part of the satellite that also contains the reactor, this shield can be used to protect the beacon as well. However, the solution to the problem of tolerating the heat of re-entry might require that the beacon be close to the shadow shield. This will subject that component to higher radiation levels than the other, more distant electronics. Such a problem is not new, however, and radiation-resistant designs are possible. Additional shielding might also be considered as the beacon is quite small. The antenna design should not be a problem since, at the frequency chosen, it need only be a few tens of centimetres across and can be buried in the airfoil.

Under the assumption that such a beacon, to be called an impact position indicator, can be produced, the operational aspects are envisioned as described below.

Knowledge of the satellite's orbit can be used to determine quite precisely its projected ground track in both time and space. Relatively simple computer programs can be used, on a personal computer, which can project graphics indicating

the ground track on maps of any convenient scale. These maps show the relationship of the ground track to populated areas.

If a signal is received by a geostationary satellite, the time of impact will be known with a high degree of precision. This time can be used with the known ground track to indicate the satellite's position as if it had remained in orbit. Such a position projected onto the Earth will be a good first approximation of the impact point. It will certainly be adequate to provide sufficient direction for any airborne monitoring equipment. It should also be sufficient to alert local authorities to broadcast a stay-inside order if the impact area covers a populated region.

Confirmation of the impact location will follow from one of the polar orbiting satellites or from other observations.

The above scenario assumes that the receiving State has its own local user's terminal and the impact point is within the country. For those States without a local user's terminal, the Convention on Early Notification of a Nuclear Accident could be used and any State with such a terminal could notify the country in which the impact has occurred of the location of the impact.

The present paper sets out only the broadest outline of a concept that has a potential to improve the early warning of the re-entry of a satellite with a nuclear power source on board.

A number of problems concerning the design of an impact position indicator have been indicated. These problems will require further study and equipment development and testing, particularly aerodynamics (optimum β) and resistance to the nuclear environment.

Systems studies on the probability of detection, accuracy and location with respect to the nuclear power source if intact and to the centroid of debris, if dispersed, are also required. Characteristics of the electronics can be found in various COSPAS/SARSAT documents. A final policy issue is also being pursued. The COSPAS/SARSAT system has been developed to assist persons in distress. COSPAS/SARSAT partners may wish to consider whether the use proposed in the present paper is appropriate. Consultation on that subject is planned. Canada's co-operating agency will be advising its counterparts on the subject and will ask for the concept to be considered at the upcoming session of the COSPAS/SARSAT council.

At the current session of the Scientific and Technical Sub-Committee of the United Nations Committee on the Peaceful Uses of Outer Space, Canada is proposing this concept for consideration as a potential solution to one of the important technical problems associated with the unplanned re-entry of nuclear power sources.

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22 February 1990

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COMMITTEE ON THE PEACEFUL USES
OF OUTER SPACE
Scientific and Technical Sub-Committee
Working Group on the Use of Nuclear
Power Sources in Outer Space

USE OF NUCLEAR POWER SOURCES IN OUTER SPACE

Safety aspects and recommendations for the use of nuclear power sources in outer space

Working paper submitted by the Federal Republic of Germany

1. Introduction

In the recent sessions of the Working Group on the Use of Nuclear Power Sources in Outer Space of the Scientific and Technical Sub-Committee, the Federal Republic of Germany presented interim results of an ongoing national study on the subject.

The study described herein was completed last year. The preliminary results were presented and discussed at an international scientific workshop held at Cologne, Federal Republic of Germany, in November 1989. The final report was submitted to the secretariat of the Committee on the Peaceful Uses of Outer Space in the form of an executive summary in January of this year.

The present working paper focuses on those study results which the Federal Republic of Germany considers important for the completion of the elaboration of the safety criteria on nuclear power sources (NPS).

The main possibilities of NPS failure and their radiological consequences for individuals, the population and the environment are summarized in chapter 2.

The recommendations of chapter 3 are based on chapter 2. They do not represent fundamentally new aspects compared to the results obtained so far in the Working Group. On the contrary, the existing recommendations are being supported, and in some aspects supplemented.

2. Main possibilities of the failure of nuclear power sources and the consequences thereof

2.1. Launch, ascent and orbital manoeuvre

2.1.1. Failures prior to or at launch are local events concerning the State on whose territory the launch takes place.

2.1.2. Failures during the ascent phase (e.g., first and second rocket stages) have effects only on the predetermined subtrack adjacent to the launching site, if and only if (a) nuclear reactors are safe against criticality under all circumstances (including impact on land or into water and submersion in water); and (b) radioisotopic generators are protected in a containment system which ensures that no radioactive material is set free in an accident.

2.1.3. Failures in injecting a space object with NPS into an Earth orbit may lead to a re-entry randomly distributed in the latitude belt corresponding to the orbit inclination, with very short prewarning time (in some cases only minutes before re-entry).

2.1.4. Failures in injecting space objects with NPS into interplanetary trajectories may lead to re-entries from highly elliptical orbits (HEO), with severe thermal and mechanical load conditions.

2.1.5. Failures in swing-by manoeuvres at the Earth during interplanetary missions may lead to re-entries from hyperbolic trajectories, with even higher thermal and mechanical load conditions.

2.1.6. Failures in the transfer of NPS from a low Earth orbit (LEO) to a sufficiently high orbit (SHO), according to current technology and to the number of subsystems involved in this manoeuvre, can occur with a probability that is not sufficiently low. This failure leads to early re-entry randomly distributed in the latitude belt corresponding to the orbit inclination. Precise pre-warning is limited by the uncertainty of the re-entry time prediction, which may in some cases be up to 10 per cent of the remaining lifetime, and by the very limited possibility of predicting the re-entry location. This failure rate can be reduced to an acceptably low failure rate by the use of redundant subsystems.

2.2. Operation and storage in a sufficiently high orbit

2.2.1. Operation of nuclear reactors in SHO from the beginning or their storage in SHO after operation and successful transfer is an acceptable practice provided that the SHO ensures an orbital lifetime sufficient to allow the radioactive fission and activation products to decay to the initial dose level of the fuel before re-entry. This also requires that highly enriched uranium 235 be used as fuel in order to minimize plutonium breeding.

2.2.2. The SHO altitude must take account of the possibility of a destructive collision with space debris occurring during the long lifetime. This probability is not negligible and may increase in the future. The SHO altitude should be such that the radioactivity of the fragments produced in a destructive collision can decay to sufficiently low levels before re-entry.

2.2.3. The operation or storage of plutonium-fuelled isotope generators in high Earth orbits would lead, even after very long times, to the re-entry of a source which was still radioactive followed by an intact impact or break-up on impact. In both re-entry cases provisions for tracking and, if required, search and retrieval or clean-up are needed.

2.3. Re-entry and radiological consequences

For the re-entry of nuclear reactors which may be either the result of a failure during orbital operations or the normal procedure after the orbital lifetime in a SHO, there are potential alternatives for the reactor design so that the nuclear fuel is:

(1) Completely dispersed in the high atmosphere in the form of aerosols;

(2) Dispersed in very small particles (sub-millimetre region) in the high atmosphere; or

(3) Enclosed in a re-entry-resisting containment system, leading to an intact impact.

In the case of an early re-entry shortly after nuclear reactor operation, methods 1 and 2 both lead to individual doses from inhalation, ingestion and radiation of the whole body well below tolerable levels, although in the case of method 2 high organ doses may occur for some individuals and countermeasures may be necessary to minimize the exposure. Method 1, however, may require a special form of fuel. Both methods may require a highly reliable active system to assure complete dispersal.

For both methods collective doses may become relatively high, and for this reason the number of events should be limited to avoid a world-wide accumulation of radioactive material. The radioactive inventory of the reactor (a function of reactor power and time of operation) should be limited with both methods to reduce the amount of radioactive material dispersed.

Method 3 may lead to a high, lethal dose for persons in the immediate vicinity of the impact and will require countermeasures in populated areas in a short time. For example, evacuation may be necessary within several hundred metres. Long-term contamination after break-up of the containment system on impact may result from volatile fission products. Therefore, one should make sure that an accidental, uncontrolled, intact re-entry of a nuclear reactor into a populated area is highly unlikely.

In all cases, early and detailed information concerning the orbital decay is essential for the preparation of countermeasures.

3. Recommendations for the safe use of nuclear power sources in outer space

In order to minimize the quantity of nuclear fuel in space and the risks involved, the use of nuclear power sources in outer space should be limited to those space missions which cannot be operated by non-nuclear energy sources in a feasible way. 1/

3.1. Nuclear reactors

3.1.1. Nuclear reactors are acceptable for operation on interplanetary missions or in sufficiently high orbits, which means that the orbital lifetime is long enough to allow for a sufficient decay of the radioactivity to about the dose level of the nuclear fuel (actinides) itself. The SHO must be such that the risks to existing and future outer space missions and of collision with other space objects are kept to a minimum. In determining SHO altitude it should be taken into consideration that, in case of destruction of the reactor, the reactor parts should also attain the required decay time before they re-enter the Earth's atmosphere. 2/

3.1.2. If nuclear reactors are used in low Earth orbits, they should be stored, after their mission, in an SHO. 2/

3.1.3. Nuclear reactors should only use highly enriched uranium 235 as fuel. The design should consider the radiological decay necessary for fission and activation products.

3.1.4. The design and the construction of the nuclear reactor should ensure that it cannot become critical before reaching the operating orbit, during all possible events such as rocket explosion, re-entry, impact with ground or water or submersion in water.

3.1.5. Nuclear reactors should not be made critical before they have reached their operating orbit or interplanetary trajectory.

3.1.6. In view of possible failures in the NPS systems or of satellites during operations in orbit (including operation for transfer into the SHO), there should be a highly reliable operational system to ensure effective and controllable disposal of the reactor. Such measures could be, for example, a back-up system to reach the SHO, a controlled and intact re-entry or other methods to be developed in the future. 2/

3.2. Isotope generators

3.2.1. Isotope generators should preferably be used for interplanetary missions and other missions leaving the gravity field of the Earth. They may also be used in Earth orbits if they are retrieved to the Earth's surface in a controlled and safe manner after the mission.

3.2.2. For re-entries into the Earth's atmosphere, which may occur after a malfunction in orbital operations, the launching organization should provide technical measures for tracking the re-entry, detection of the re-entered radioactive material and, on request, for retrieval or clean-up operations.

3.2.3. Isotope generators should be protected by a containment system which withstands the heat and the aerodynamic forces during the re-entry in the upper atmosphere under all possible orbital conditions, i.e., also from highly elliptical or hyperbolic orbits if relevant. Upon ground impact, the containment system and the physical form of the isotope should ensure that no radioactive material is introduced (in soluble, volatile, aerosol or micro-particle form) into the environment so that the impact area can be completely cleared of radioactivity by a retrieval operation.

3.3. Design goals for radiation protection

3.3.1. The general nuclear safety objective for NPS in space is to protect individuals, society and the environment against radiological hazards. Therefore, the design of the NPS should ensure that the hazards to the population - operational or accidental - are reduced to an acceptable level. 3/

3.3.2. During normal operation, including all anticipated situations, the appropriate radiation protection objective recommended by the International Atomic Energy Agency (IAEA) should be observed. It is recommended that during normal operation the individual dose should not exceed 10 μSv and the collective dose 1 man-Sv. 4/

3.3.3. In case of accidents, the NPS safety system should ensure that the probability of serious radiological consequences is extremely small. To reduce exposures in accident scenarios, the design of the NPS safety system should take into account the principles and limits recommended by the International Commission on Radiological Protection (ICRP). The NPS safety system should ensure a regional limitation of radiation exposure and a limitation of the individual dose to 1 mSv. 5/

3.3.4. The design of NPS should also ensure with high reliability that the generation of radiation or radioactive contamination does not significantly pollute outer space. 6/

Notes

1/ See A/AC.105/C.1/WG.5/L.21 and Add.1 and 2.

2/ See the recommendations of the Working Group on the Use of Nuclear Power Sources in Outer Space as contained in the report on the work of its seventh session; A/AC.105/429, annex III, paras. 16 and 17.

3/ Ibid., paras. 19 and 24.

4/ Ibid., paras. 22, 23 and 25.

5/ Ibid., paras. 22 and 26.

6/ Ibid., para. 27.

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COMMITTEE ON THE PEACEFUL USES
OF OUTER SPACE
Scientific and Technical Sub-Committee
Twenty-seventh session
Working Group on the Use of Nuclear
Power Sources in Outer Space

DRAFT REPORT OF THE WORKING GROUP ON THE USE OF NUCLEAR POWER SOURCES IN OUTER SPACE ON THE WORK OF ITS EIGHTH SESSION

I

1. The Working Group on the Use of Nuclear Power Sources in Outer Space, reconvened in accordance with General Assembly resolution 44/46, paragraph 12, held its eighth session at United Nations Headquarters from 5 to ... March 1990. Mr. J. H. Carver (Australia) served as its Chairman.

2. The Working Group held ... meetings. A list of the experts who attended the session is given in document A/AC.105/C.1/WG.5/INF.1.

3. The Working Group had before it replies from Austria, Czechoslovakia, Finland, the Federal Republic of Germany, Japan, Pakistan, Sweden, United Arab Emirates and the Union of Soviet Socialist Republics, to the Secretary-General's note verbale dated 30 June 1989 (A/AC.105/C.1/WG.5/L.24, Add.1-3 and Add.2/Corr.1) as well as working papers and studies submitted by Canada (A/AC.105/C.1/WG.5/L.26) and the Federal Republic of Germany (A/AC.105/C.1/WG.5/L.25 and 27).

4. Following an exchange of views, the Working Group adopted the present report at the conclusion of its meeting on ... March 1990.

II

5. The Working Group reviewed the conclusions it had reached in its previous reports, in particular, that of its third session (A/AC.105/287, annex II).

6. The Working Group noted that countries launching nuclear power sources (NPS) were conducting safety assessments of those systems and were making those assessments publicly available. In particular, the Working Group took note of the description of the safety assessment process for the Galileo interplanetary mission as presented by the United States of America.

7. Some delegations stated that since there was a reasonably high probability of collision of spacecraft carrying NPS with space debris in the altitude band of 800 to 1,000 km, it was essential to study this question and to develop methods to minimize possible radiological hazards. This might require the development of new technologies for prevention of the creation of new debris, monitoring of the situation or even removal of space debris from orbit.

8. The view was expressed that the consequences of a spacecraft with NPS on board colliding with space debris could be studied using a variety of collision models. The risk of collisions should be studied particularly in the altitude range of 800 to 1,100 km, where most nuclear sources, together with a large number of other satellites and the maximum density of space debris, are to be found. Since different types of objects could collide, methods have to be developed for calculating the effects of elastic and non-elastic impacts, and of spacecraft destruction with the scattering of secondary fragments. Numerical computation could reveal changes in the orbital lifetimes of the resulting objects and their interaction with the atmosphere.

9. Some delegations emphasized that space missions with NPS should be justified by the radiation protection criteria recommended by the International Commission on Radiological Protection (ICRP) in terms of benefit versus risk. The view was expressed that the results of this justification procedure should be made publicly available.

10. It was observed that there was not an urgent need to seek quantitative limitations to the amount of radioactive material either in individual nuclear devices or in the total radioactive inventory in orbit, as long as the number of space missions employing NPS was small and the nuclear devices had a radioactivity content similar to that currently used.

11. Some delegations expressed appreciation for the above-mentioned papers submitted by Canada, the Federal Republic of Germany and the Union of Soviet Socialist Republics (A/AC.105/C.1/WG.5/L.24/Add.2, and L.25-27).

12. During the consideration of document A/AC.105/C.1/WG.5/L.27, a presentation was made of the provisions contained in document A/AC.105/C.2/L.173, and a proposal was made that Principle 3 as contained in that document be supplemented to the effect that as soon as technology permits, any State launching a space object with a nuclear power source on board shall include, as part of the component of the space object containing the nuclear power source, an impact position indicator, that, for example, will transmit electronic signals to facilitate location of the impact point with a high degree of accuracy, and provide time of impact on the Earth's surface, identify the launching State and the space object in question.

III

13. The Working Group agreed on the following recommendations for the safe use of nuclear power sources in outer space. In order to minimize the quantity of radioactive material in space and the risks involved, the use of nuclear power sources in outer space should be restricted to those space missions which cannot be operated by non-nuclear energy sources in a reasonable way.

1. Design goals for radiation protection

1.1 The general radiation safety objective for NPS in space is to protect individuals, population as a whole and the biosphere against radiological hazards. Therefore, the design of NPS should ensure, with a high degree of confidence, that the hazards - in all foreseeable circumstances, operational or accidental - are kept below an acceptable level.

The design of NPS should also ensure with high reliability that radioactive material does not significantly pollute outer space.

1.2 During normal operation, including re-entry from the SHO, the appropriate radiation protection objective for the public recommended by the International Commission on Radiological Protection (ICRP) should be observed. It is recommended that during such normal operation there should be no significant radiological exposure.

1.3 To limit exposures in accident scenarios, the design of the NPS safety system should take into account relevant international guidelines recommended by the International Commission on Radiological Protection (ICRP).

The design goal for the NPS safety system should be with a high degree of confidence a regional limitation of radiation exposure and a limitation of the individual dose to the principal limit of 1 mSv in a year. However, it is permissible to use a subsidiary dose limit of 5 mSv in a year for some years, provided that the average annual effective dose equivalent over a lifetime does not exceed the principal limit of 1 mSv in a year. Future modifications of the recommendations of ICRP should be applied.

The NPS safety system should also ensure that the probability of serious radiological consequences is extremely small.

1.4 For NPS-re-entries into the Earth's atmosphere, which may occur after a malfunction in orbital operations, the launching State should provide technical support to identify the location of re-entry and impact, to detect the re-entered radioactive material and, on request, to carry out retrieval or clean-up operations.

2. Nuclear reactors

2.1 Considering the risk of re-entry nuclear reactors are acceptable for operation on interplanetary missions or in sufficiently high orbits (SHO). The SHO is one in which the orbital lifetime is long enough to allow for a sufficient decay of the fission products to about the activity of the actinides. The SHO must be such that the risks to existing and future outer space missions and of collision with other space objects are kept to a minimum. In determining SHO altitude it should be taken into consideration that, in case of destruction of the reactor, the reactor parts should also attain the required decay time before they re-enter the Earth's atmosphere.

2.2 If nuclear reactors are used in low Earth orbits, they should be stored, after their mission, in a SHO.

2.3 Nuclear reactors should only use highly enriched uranium 235 as fuel. The design should consider the radiological decay of the fission and activation products.

2.4 The design and the construction of the nuclear reactor should ensure that it cannot become critical before reaching the operating orbit, during all possible events such as rocket explosion, re-entry, impact on ground or water or submersion in water.

2.5 Nuclear reactors should not be made critical before they have reached their operating orbit or interplanetary trajectory.

2.6 In view of possible failures in the NPS systems or of satellites during operations in orbit (including operation for transfer into the SHO), there should be a highly reliable operational system to ensure effective and controllable disposal of the reactor. Such measures could be, for example, redundancies in the orbital transfer system to reach the SHO, or other methods to be developed in the future.

3. Isotope generators

3.1 Isotope generators should preferably be used for interplanetary missions and other missions leaving the gravity field of the Earth. They may also be used in Earth orbits if they are stored after mission end in a high orbit. Ultimate disposal, would however, still be required.

3.2 Isotope generators should be protected by a containment system which withstands the heat and the aerodynamic forces during the re-entry in the upper atmosphere under all possible orbital conditions, i.e., also from highly elliptical or hyperbolic orbits if relevant. Upon ground impact, the containment system and the physical form of the isotope should ensure that no radioactive material is scattered (in soluble, volatile, aerosol or micro-particle form) into the environment so that the impact area can be completely cleared of radioactivity by a recovery operation.